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FEASIBILITY DEMONSTRATION OF A NON-  
POLLUTANT SYNTHETIC FIRE FIGHTING  
TRAINER

Edmund Swiatosz, et al

Naval Training Equipment Center  
Orlando, Florida

December 1974

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Technical Report: NAVTRAEQUIPCEN IH-241

FEASIBILITY DEMONSTRATION OF A NON-POLLUTANT  
SYNTHETIC FIRE FIGHTING TRAINER

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December 1974

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flame response and acceptability of stack gas concentrations. The potential advantages in addition to its clean burning capabilities included (1) safe toxic levels (2) quick shutdown and start-up and (3) flexible control of extinguishment and reflash rates.

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SECTION I

INTRODUCTION

The Navy's fire fighting training facilities include burning diesel oil which results in objectional volumes of thick, black smoke particulates or soot along with gaseous pollutants. Recent data (1) indicates that these oil fires may present a severe potential health hazard particularly to instructor personnel exposed to the multitude of chemicals in the soot.

The current methods used by the Navy to reduce smoke emissions from oil fire trainers are the afterburner and water spray systems. These reduce smoke particulates by about 90 percent compared to about 99 percent particulate reductions available on some recent large size particulate filtration methods.

Extensive and costly afterburner systems have been installed at San Diego and Treasure Island Naval Stations. These provide smoke abatement facilities for forecandle, boiler room, engine room and flight deck simulators but no open fire trainers. In an attempt to provide a cost effective trainer a prototype water spray method (2), developed for the Naval Training Equipment Center, has been installed at the Fleet Training Center in Norfolk, Virginia. Both methods, however, retain diesel oil as a fire source with questionable performance to meet possible future restrictions on environmental pollution and occupational safety.

The use of a gaseous fuel has been proposed (3) in conjunction with a logic control circuit as an alternate method of reducing pollution. In addition to providing a clean burning fuel with relatively few gaseous products, this system would have several potential advantages. These include capabilities for quick start up and shut down, flexible control of extinguishment and reflash rates, and monitoring of trainee performance. Hence, it would be possible to provide adaptive type training and features such as temporarily stopping a training session for detailed corrective instruction. The feasibility of this system has been studied under NAVTRAEQUIPCEN Research Task 1734. This report documents the results of this task and includes:

- A concept formulation for using an array of computer controlled gas burners for fire fighting simulation.
- The assembly and test of a digital control unit and small scale multiple gas burner demonstrator.
- The flame characteristics and stack gas analysis from a single full size burner under various experimental conditions.

<sup>1</sup> Hill, T.A., Siedle, A.R., and Roger Perry, Navy Preventive Medicine Unit 2, Norfolk, Va, Hazards of a Fire-Fighting Training Environment, American Industrial Hygiene Association Journal, June 1972, p. 423-430.

<sup>2</sup> Goldsmith, A. and Wakely, H.G., NAVTRAEQUIPCEN Rpt 69-C-0181, Fire Simulation Concepts, Feb 1970.

<sup>3</sup> Wolff, H.H., Patent No. 3,675,342, Fire Fighting Trainer, July 1972.

## SECTION II

## STATEMENT OF THE PROBLEM

## GENERAL

The purpose of this program is to determine the feasibility of a fire fighting trainer concept involving, (1) the use of a clean burning gaseous fuel in place of the presently used diesel oil and, (2) a logic circuit digital control unit for providing automatic response of an array of gas burners to an applied extinguishment agent.

## GASEOUS FUEL CHARACTERISTICS

The extinguishment of a premixed gaseous fuel and air fire would not be accomplished by direct application of a water spray. Hence sensors must be used to detect the extinguishment agent and controls provided for artificially extinguishing the flame by shutting off the gas. This requires determination of parameters which will provide realistic flame characteristics. Realism will also depend on the modular spacing of the array of burners and sensors, and the required time delays for extinguishment and reflash, i.e., interaction of adjacent burners to produce flame spread over an area. These characteristics should be responsive to the various actions of sweeping the hose water over the simulated area of fire. It is also necessary to verify, safe concentrations of stack gases for various parameters such as air-fuel ratio, top stack exhaust opening, bottom draft opening, and application of hose water.

## DIGITAL CONTROL UNIT

The special purpose digital control unit is to control the array of gas burners in a manner to simulate a variety of fires applicable to Navy Fire Fighting Training. The two primary characteristics to simulate is the rate at which the fire is extinguished and the rate at which a fire will spread or reflash when not continually controlled. These two rate characteristics should be easily adjustable by an instructor with a simple control varying all burners simultaneously. Simulation of the various fuel types, extent of fuel available, and the fire temperature is achieved through variation of the extinguish and reflash rates. The character of the extinguishing process should include a noticeable decrease in flame intensity when water is applied to it, eventual removal of all flame in the area where water is applied, and a flashback of the flame if water is not applied long enough after the flame is out to cool the remaining fuel. The character of the reflash process should cause a nonburning area to be ignited if a neighboring area is burning and no water is applied to it for an appropriate time period depending on the type fuel and temperature of the fire being simulated.

## SECTION III

## PROCEDURE

## GENERAL

The program effort was divided into separate procedures leading to (1) the logic design and build of a digital control unit for automatic operation of the gas burners, (2) construction of a small scale multiple array of burners for demonstrating the system concept, and (3) determining flame characteristics and stack gas measurements of a single full size burner.

The general operation of the system is indicated in the block diagram in figure 1. As fire hose water is applied, samples of water are collected and diverted to the water sensors which detect the quantity and location of the applied water. Signals from the sensors and the solenoid gas valves are fed to the digital control unit which determines the degree of extinguishment for a particular burner. This would depend on the duration of the applied water, the on or off state of the adjacent burners, and on the instructor settings for extinguishment and reflash times at the control console. The instructor settings would depend on the average times of extinguishment and reflash comparable to that in an actual fire fighting trainer and the modular spacing of the burners and sensors. The spacings between the burners (and sensors) would, in turn, be determined by the area coverage of the applied extinguishment agent.

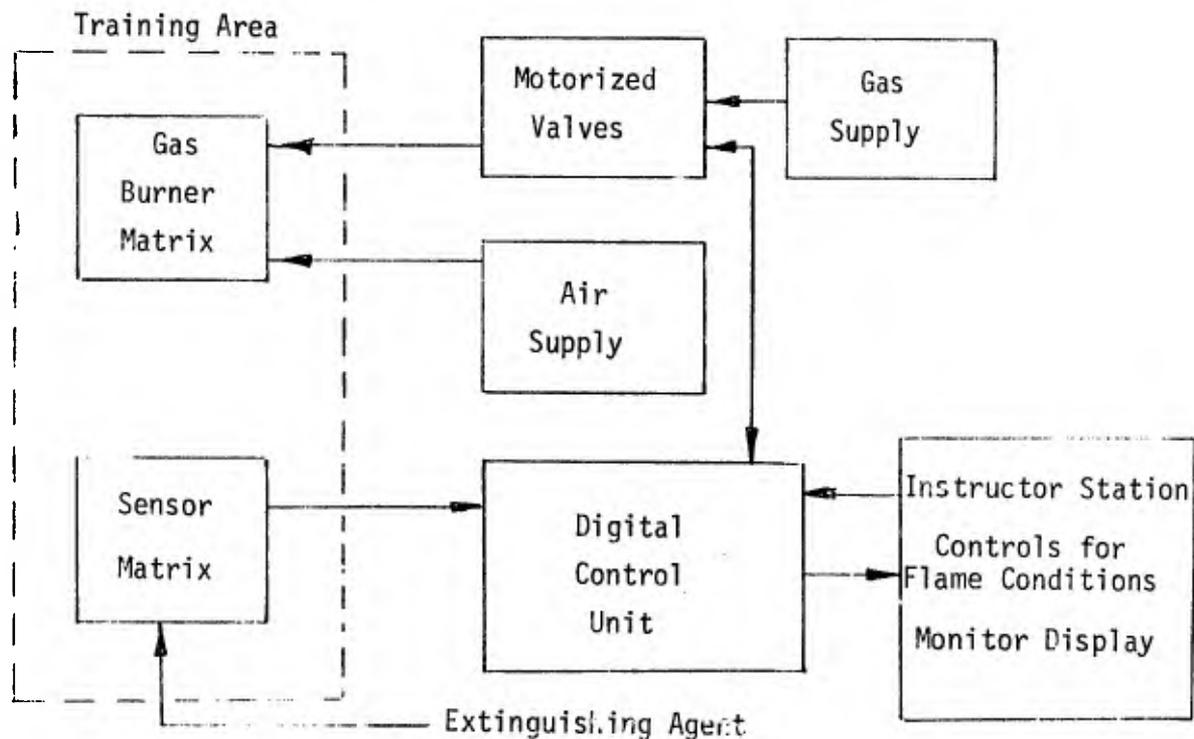


Figure 1. Block Diagram Synthetic Fire Fighting Trainer System

## DIGITAL CONTROL UNIT APPROACH

A modular design based on digital logic circuitry was selected as the design approach for the control unit shown in figure 2. A standardized module was designed so that any size fire simulator could be built simply by providing one module for each burner which is called the "A Module." A second standardized module was designed called the "B Module" and is used to interface any two "A Modules" which are adjacent neighbor burners to provide the reflash or fire spreading function. Figure 3 shows the logic functions performed by the two modules. Each module contains a binary counter and logic circuitry to generate the delay times required by the extinguish and reflash functions. The delay times for various types of fire simulation is obtained by varying the clock rates which go to the module counters. The variable rate extinguish clock is distributed to all "A Modules." The variable rate reflash clock is distributed to all "B Modules." This method of obtaining variable delay times provides a consistency and uniformity not readily obtained by other delay methods such as resistor capacitor time constants.

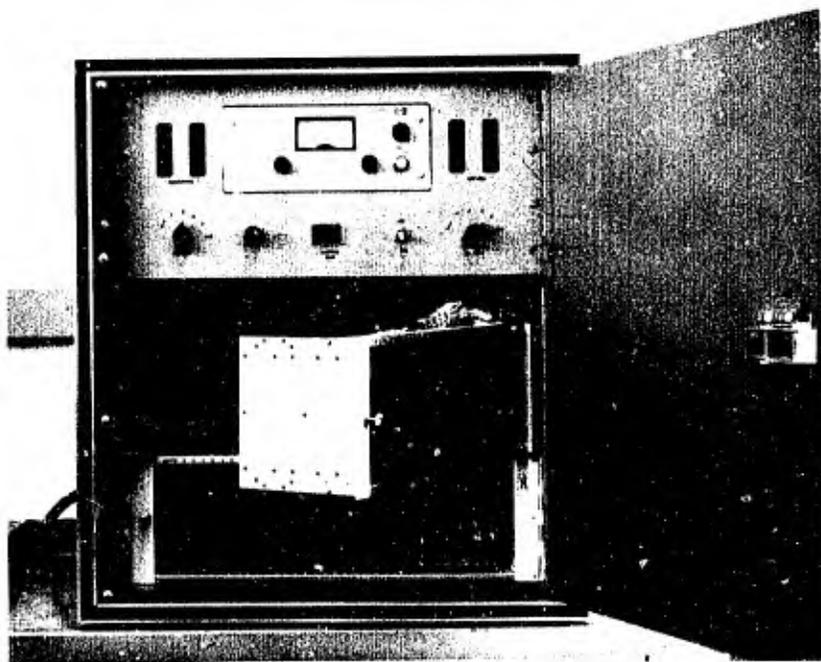
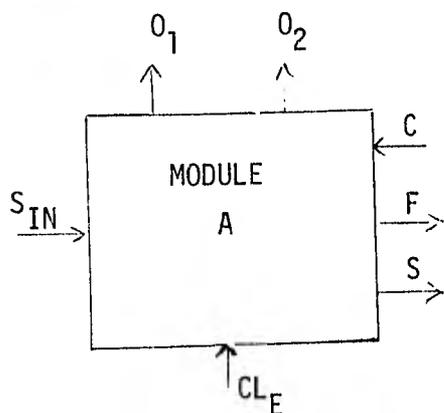


Figure 2. Digital Control Unit

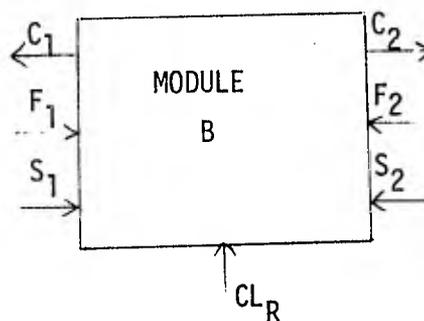
DEFINITION OF TERMS:

- F = Fire ON
- C = Clear the Fire Control Flip Flop
- S =  $S_{IN}$  = Sensor activated by extinguishment
- $CL_E$  = Clock, Extinguish
- $CL_R$  = Clock, Reflash
- $O_1$  = Output No. 1 for 1/2 intensity command
- $O_2$  = Output No. 2 for 0 intensity command



MODULE A LOGIC FUNCTIONS

$$\begin{aligned}
 O_1 &= S_{IN} + O_2 \\
 O_2 &= S_{IN}(4 CL_E) + \bar{F} \\
 S &= S_{IN} \\
 F &= C \\
 \bar{F} &= S_{IN} (8 CL_E)
 \end{aligned}$$



MODULE B LOGIC FUNCTIONS

$$\begin{aligned}
 C_1 &= \bar{F}_1 F_2 \bar{S}_1 \bar{S}_2 (8 CL_R) \\
 C_2 &= F_1 \bar{F}_2 \bar{S}_1 \bar{S}_2 (8 CL_R) \\
 \bar{C}_1 + \bar{C}_2 &= S_1 + S_2 + F_1 F_2 + \bar{F}_1 \bar{F}_2
 \end{aligned}$$

Figure 3. Module Logic Functions

The "A Module" is the basic logic unit which accepts the extinguishment sensor signal and provides output commands to control the fire burners. Upon receipt of the sensor signal which is activated by water or other extinguishment a gate is opened allowing an eight-stage counter to begin counting clock pulses in the forward direction. This clock, called the extinguish clock, has its rate set by the instructor depending on the type fire being simulated. The counter will continue to count up to eight counts if the sensor signal remains activated and will then latch itself until a clear command is received. If the sensor signal is removed prior to eight counts, internal logic will cause the counter to count down to zero and hold until once again activated by the sensor signal. If the sensor signal is received during this countdown, the counter will immediately resume its forward counting toward an eight count. The "A Module" has two outputs which are in the zero state if no sensor signal is applied and the counter is below four counts. In this condition, the fire will burn at full intensity. Upon receipt of a sensor signal, output No. 1 is activated which reduces the fire to one-half intensity. When the counter reaches a four count, output No. 2 is activated and the fire is out. Internal logic keeps output No. 1 activated whenever output No. 2 is activated. If the sensor signal does not remain activated until an eight count is reached, the counter will count back down and outputs No. 1 and No. 2 will be deactivated when the count goes below four, thus, reigniting the fire.

The "A Module" interfaces with other "A Modules" through an interface logic unit "Module B." An "A Module" whose fire is out will be reignited by an adjacent "A Module" whose fire is burning for a time period specified in the "B Module." There are three connections on the "A Module" which are used with any adjacent module and all adjacent modules use these same three terminals. One of the three terminals is an input which, if grounded, will clear the "A Module" counter and thus reignite the fire. The other two terminals are outputs which indicate if the sensor signal is activated and if the counter has an eight count, thus telling if the fire is out or not.

The "B Module" is an interface logic unit between two adjacent "A Modules" which will reignite an "A Module" if its neighbor module is burning for a specified period of time. The "B Module" is bilateral in that it will perform its function in either direction between the two "A Modules." The "B Module" contains an exclusive - or logic circuit - which determines if one of the two "A Modules" is burning when the other is not. When this condition exists an eight-stage counter begins counting clock pulses. This clock called the reflash clock has its rate set by the instructor depending on the characteristics of the fire being simulated. When the counter reaches an eight count a clear signal is sent to the "A Module" whose fire is out thus reigniting it. If the sensor signal of either "A Module" is activated, the counter is reset to zero. This prevents the extinguished "A Module" from being reignited when water is being applied to its extinguished burner and an adjacent burner is burning.

A 24-module control unit in a 4- by 6 matrix array was selected for the feasibility design. This would provide an adequate size array to conduct tests on interacting effects between modules. Thirty-five interfacing

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"B Modules" were required to connect the 24 "A Modules" into a rectangular grid array. Supporting electronics for the module array include power supply, two variable digital clocks, and a control panel.

A display box shown in figure 4 and consisting of 24 lights and 24 photo-cells was fabricated to simulate the burners and water sensors, respectively. With the display interfaced with the 24 module control unit all modules can be controlled and their output displayed. This provided both a visual demonstration of the digital control unit functions and a valuable checkout tool for debugging the control unit during fabrication.

An interface box shown in figure 5 was built to provide the power drive signals for a six burner demonstration unit. Each burner was controlled by a dual solenoid to provide gas pressure states of high, low, and off. The interface box contained the necessary relays and power supplies to interface the low voltage control unit with the burner solenoids. The box also provided a manual mode for operating the solenoids without the digital control unit.

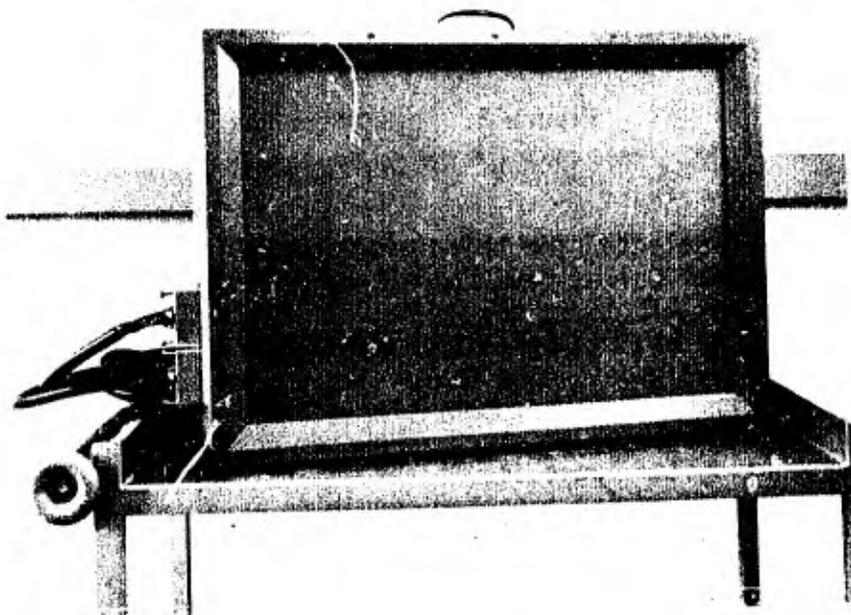


Figure 4. Display Box

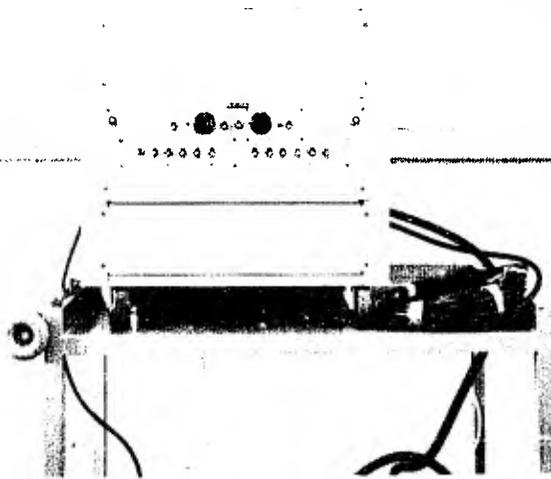


Figure 5. Interface Box

The logic type selected for the digital control unit was diode transistor logic card assemblies called Blue Chip  $\mu$  Logic DTL manufactured by Data Technology Corporation. DTL logic easily satisfied the low speed requirement of the control unit and has higher noise immunity and lower power requirements than most other logic types. The use of logic card assemblies significantly reduced assembly time. However, they also resulted in a more complex wiring layout than could have been obtained if custom designed assemblies were used. The added cost of custom logic assemblies was not warranted for this prototype but should be considered for a system requiring a large quantity of modules. The logic circuit for each of the modules is shown in figures 6 and 7.

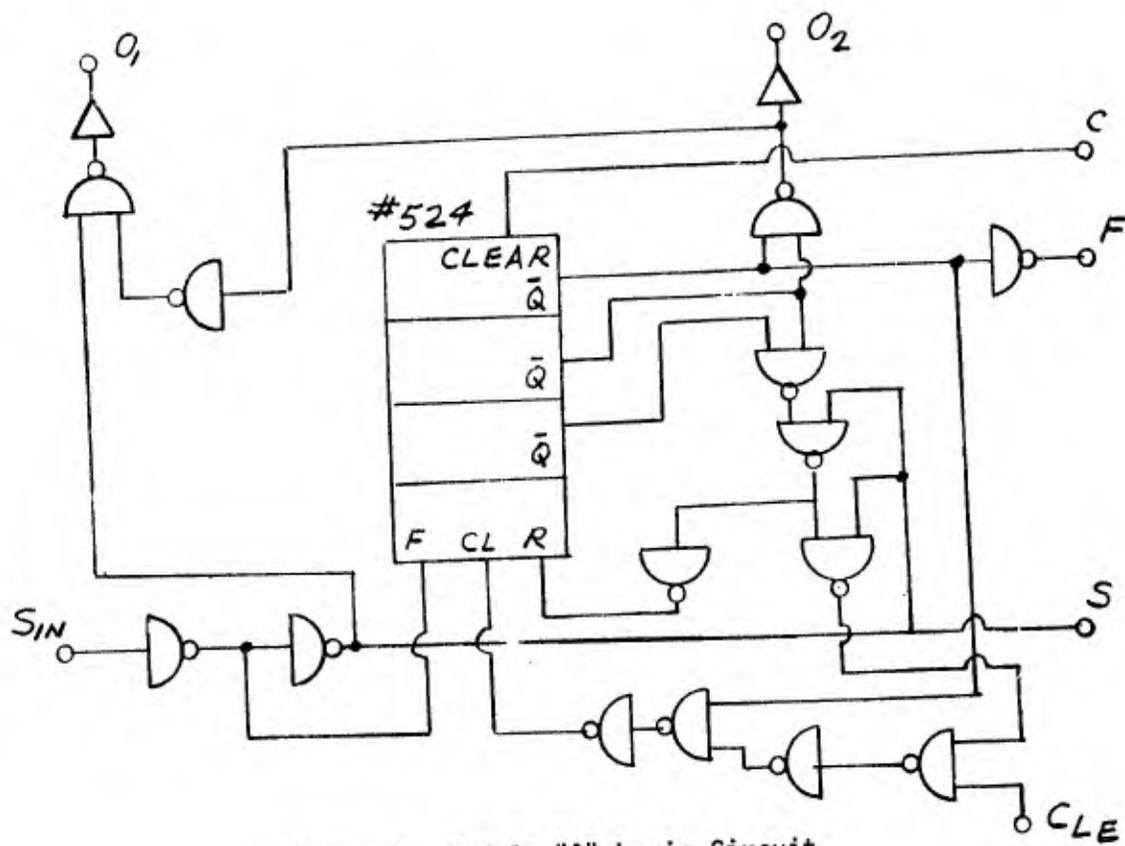


Figure 6. Module "A" Logic Circuit

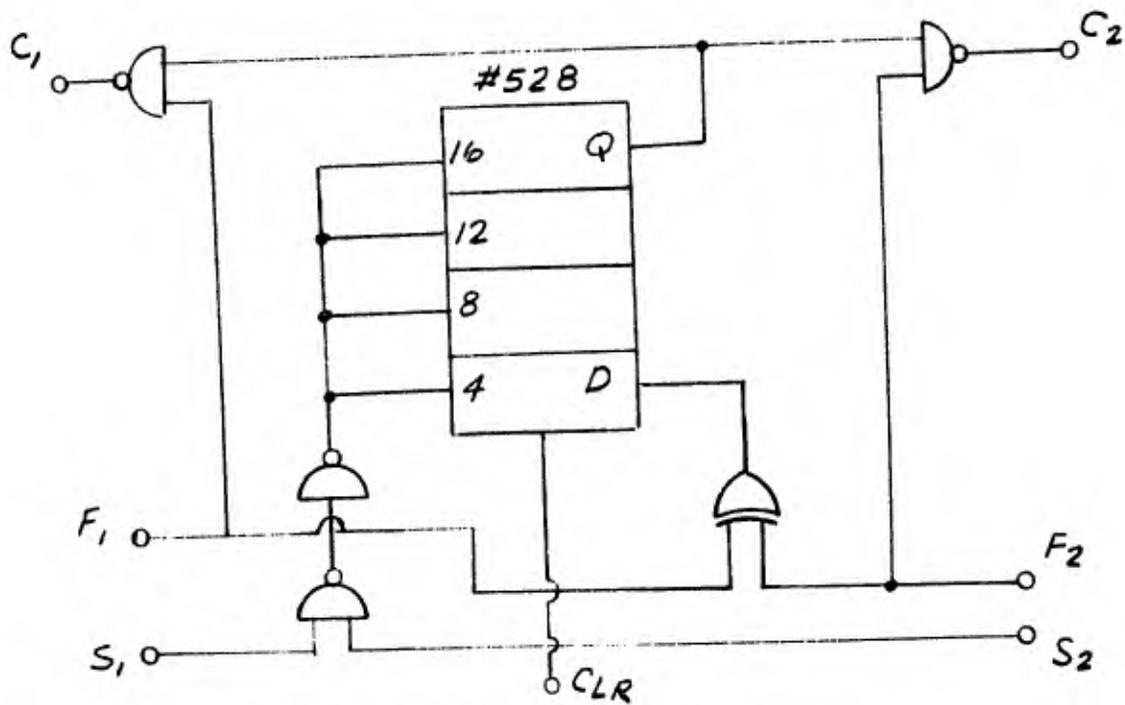


Figure 7. Module "B" Logic Circuit

## SMALL SCALE MULTIPLE BURNER EQUIPMENT

A small scale model of a burner array was used to demonstrate the digital control operation of the system. The general arrangement of the unit as shown in figure 8 was constructed using standard commercial equipment. The unit included six 350,000 btu per hour horizontally mounted burners to produce a 2- by 3-foot flame area. Experimentation was used to design and horizontally position the nozzle outside the flame area with flame deflectors to spread the fire. The bouyant hot flames provided the upward direction of the flames which passed vertically through a steel grating to simulate a burning surface. Each burner was controlled by a two-rate solenoid gas valve which would extinguish the burner with successive signals from the digital control unit. The first stage was adjusted so an initial signal would reduce the gas output about 50 percent and a second signal would shut the valve completely.

A pilot light provided the reignition capability. An automatic electric arc re-light maintained a lighted pilot under windy conditions. Thermocouple sensors were provided with safety shut-off valves for burner shutdown in the event that the pilot light was extinguished.

The burner nozzles were located outside the flame area to minimize exposure to direct hose water spray. A series of water collectors, one for each burner, were used to divert water to a float switch sensing device. The collectors were shallow in depth to minimize sensor deactivation time-lags due to water run-off after removal of the hose water. The sensor contained a level switch consisting of a permanent magnet-equipped float which moved with the water level to activate a hermetically sealed reed switch. This type of sensor was selected for availability and convenience and is by no means a recommended approach. As discussed later in this report, other types of sensors will have better potential reliability and performance advantages.

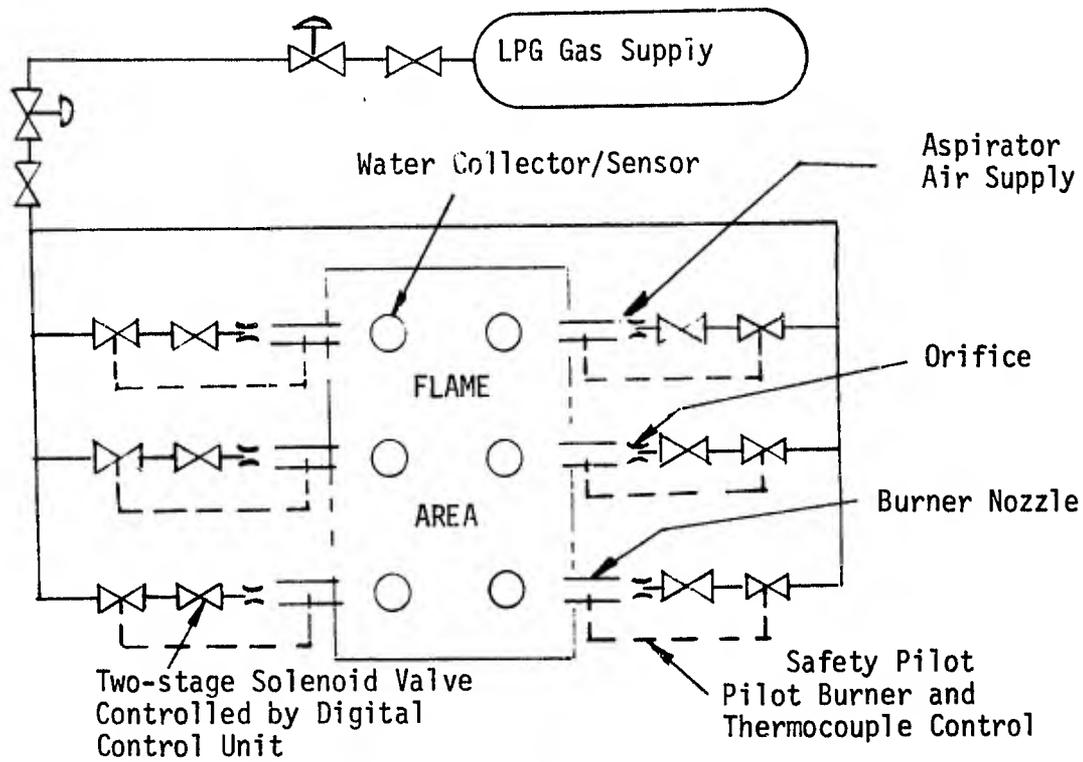
## FULL SIZE BURNER

In addition to the six-burner demonstrator, a full-size horizontal burner (4) equipped with an air blower and rated for four million btu per hour was selected for experimental flame and stack gas measurements. The burner, as shown in figure 9, was purchased as a prepackaged unit and normally has a constant gas-air ratio feature. This was deleted in order to manually set the various gas-air ratios for individual tests. A propane gas supply was provided under a two-stage reduction to seven-inch water pressure at the burner. The fuel is mixed with the primary air supply from the blower prior to ignition. Fuel quantities were selected to provide a flame coverage up to about 4- by 4-foot area and up to about 10-foot flame height.

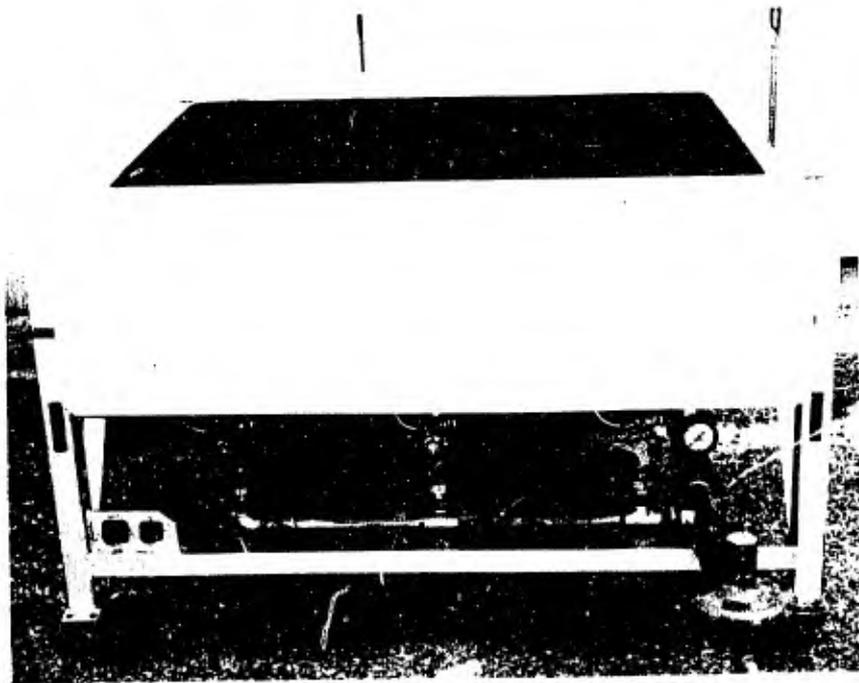
<sup>4</sup> Eclipse Bulletin H-89, Eclipse Gas Burner No. 140-IP, Eclipse Fuel Engineering Co., Rockford, Illinois.

To facilitate control of the secondary air conditions, a 6- by 13-foot high enclosure was constructed as shown in figure 10. This would enclose flames comparable to one of the burners in a multiple array required for a full size prototype trainer. The enclosure roof provided stack exhaust openings of 10 inches, 15 inches, 20 inches, and 24 inches diameter.

The test setup as shown in figure 11 included metering of the gas and air supply to the burner. Gas and air temperatures and thermocouple measurements within the flame enclosure were also provided. These provided the means for obtaining parameters of gas rates, air-fuel ratios, and effects of bottom draft and upper roof openings on stack gas measurements. Stack gas measurements for CO, CO<sub>2</sub>, O<sub>2</sub>, NO<sub>x</sub> and hydrocarbons were made using "National Mine Service" detector tubes. Samples were taken 10 feet above the burner nozzle centerline at the exhaust exit opening of the enclosure except during open air tests when the sample tube was 6-1/2 feet above the burner nozzle.



(a) Schematic



(b) Completed Assembly

Figure 8. Six-Burner Demonstrator

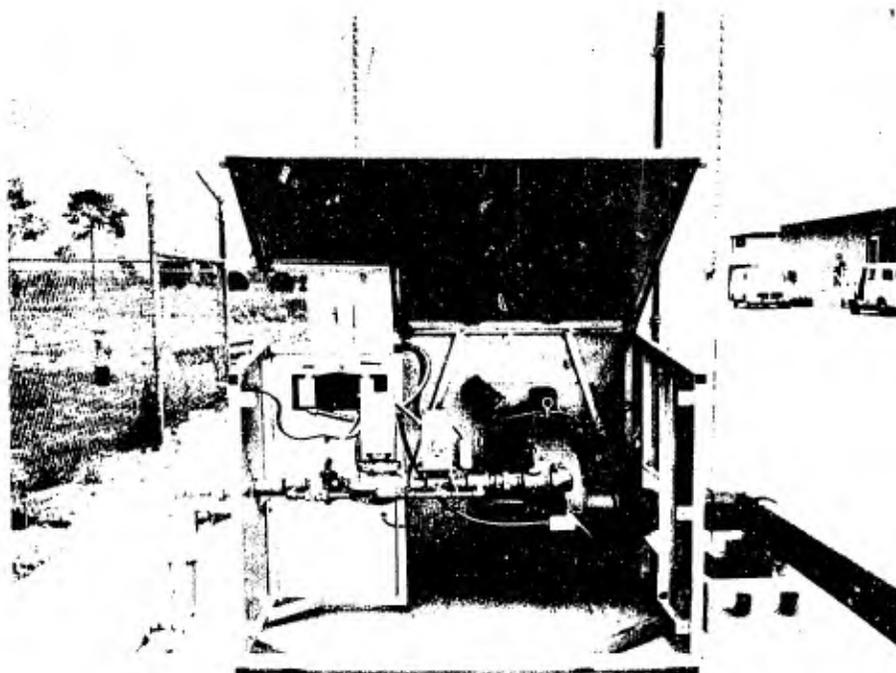


Figure 9. Burner and Control Assembly



Figure 10a. Burner Enclosure Arrangement

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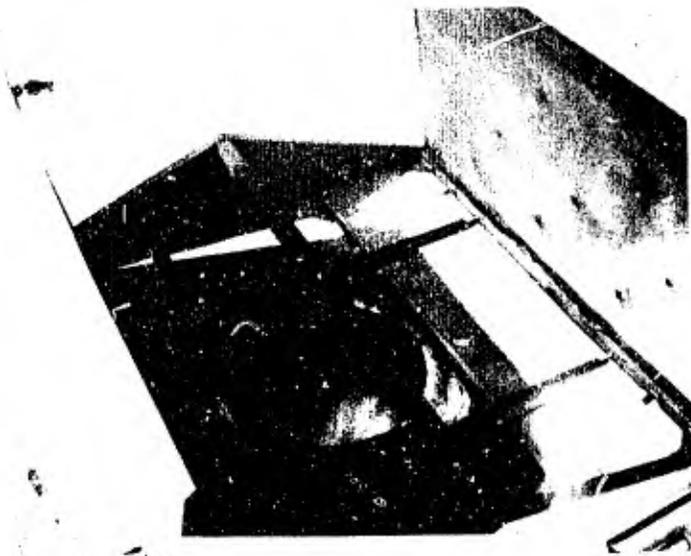


Figure 10b. Top View Burner Enclosure Showing 24-inch Diameter Stack Exhaust and Sampling Tube



Figure 10c. Propane Flame for Horizontal Burner

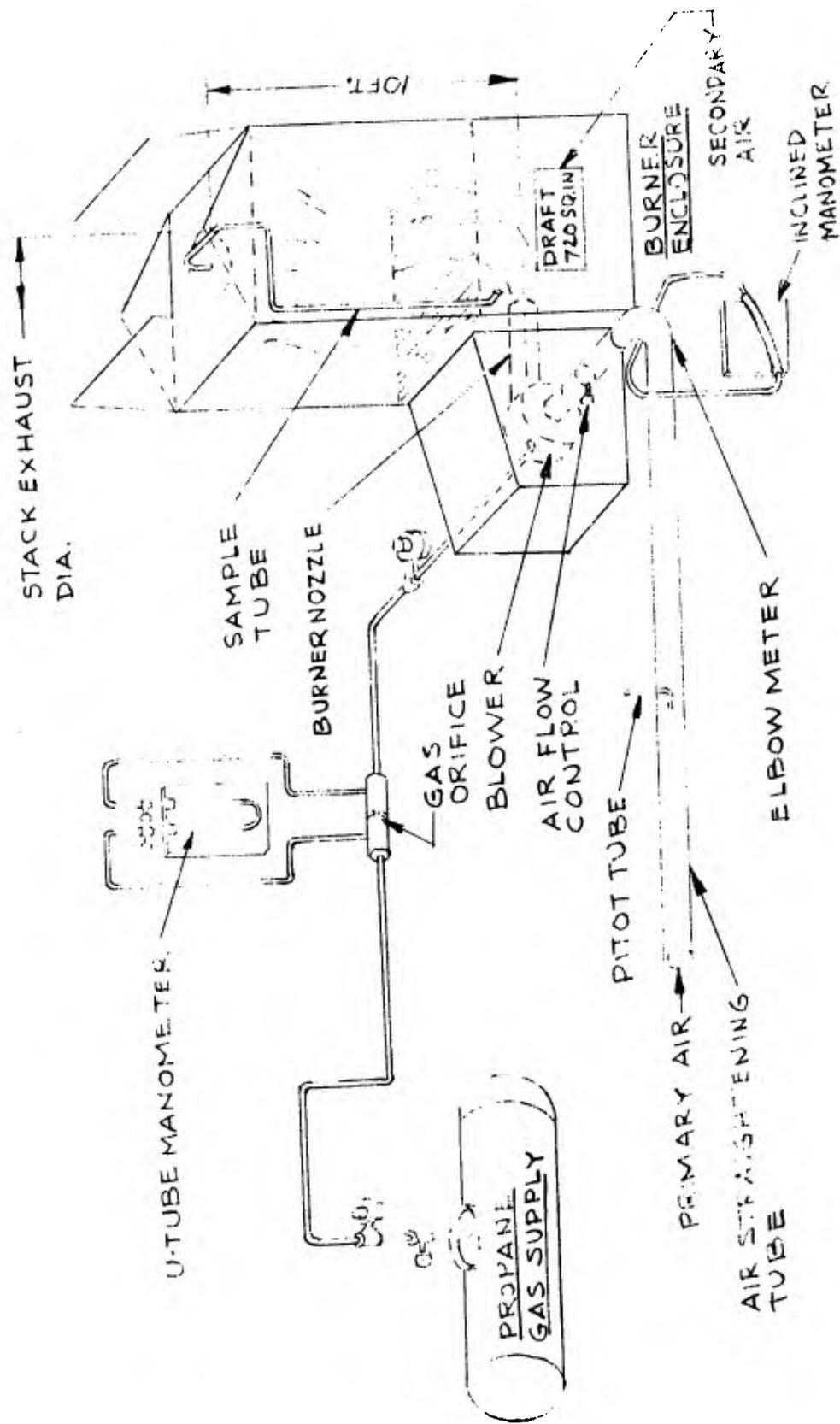


Figure 11. Schematic of Test Setup for Stack Gas Measurement

## SECTION IV

## RESULTS

## BURNER EQUIPMENT PERFORMANCE

Both the six-burner and full size burner assemblies demonstrated clean and reliable operation after initial troubleshooting and minor modifications. The six-burner demonstrator and digital control unit system responded realistically in providing automatic extinguishment to the hose water.

The results of testing for flame size are indicated in figures 12 and 13. These show maximum flame sizes of 50-inch height by 14-inches diameter for the smaller burner and up to 10- to 13-foot flame heights with 5- by 5-foot flame area for the full size burner under conditions of low air-fuel ratio.

The effects of air-fuel ratio on flame size and turbulence is also illustrated in figure 14. Figure 14c indicates realistic simulation at low air-fuel ratios. In contrast as the air-fuel ratio is increased as in figure 14 (a), a relatively short, steady, hot flame resulted which would be unsuitable for fire fighting training.

## DIGITAL CONTROL UNIT

Each of the 24 assembled modules was tested for each of the selected extinguish time constants of 1/2, 1, 2, 4, and 8 seconds. Each of the thirty-eight interface modules was tested for operation in both directions at each of the selected reflash time constants of 1/2, 1, 2, 4, and 8 seconds. This was a total of 500 individual tests which were rapidly performed through use of the display unit to provide the input and output responses. The display unit pinpointed the exact locations of any faults and minimized troubleshooting time. Since only two types of modules are used, a rapid plug-in replacement can minimize equipment down time. All modules were debugged and satisfactorily passed the tests.

The digital control unit was tested using the display unit for various combinations of extinguish and reflash time constants. The simulated fire could be extinguished as long as the extinguish time constant was shorter than the reflash time constant. As the ratio of reflash time constant to extinguish time constant was increased, the fire was less and less difficult to put out. A very hot fire could be simulated by making the extinguish time constant long, and nearly equal to the reflash time constant. This would require water to be put on for a long time to put the fire out and a continuing respraying of the extinguished perimeter area to prevent reflash. Cooler fires and various fuel type fires were simulated by selecting the appropriate time constant combinations.

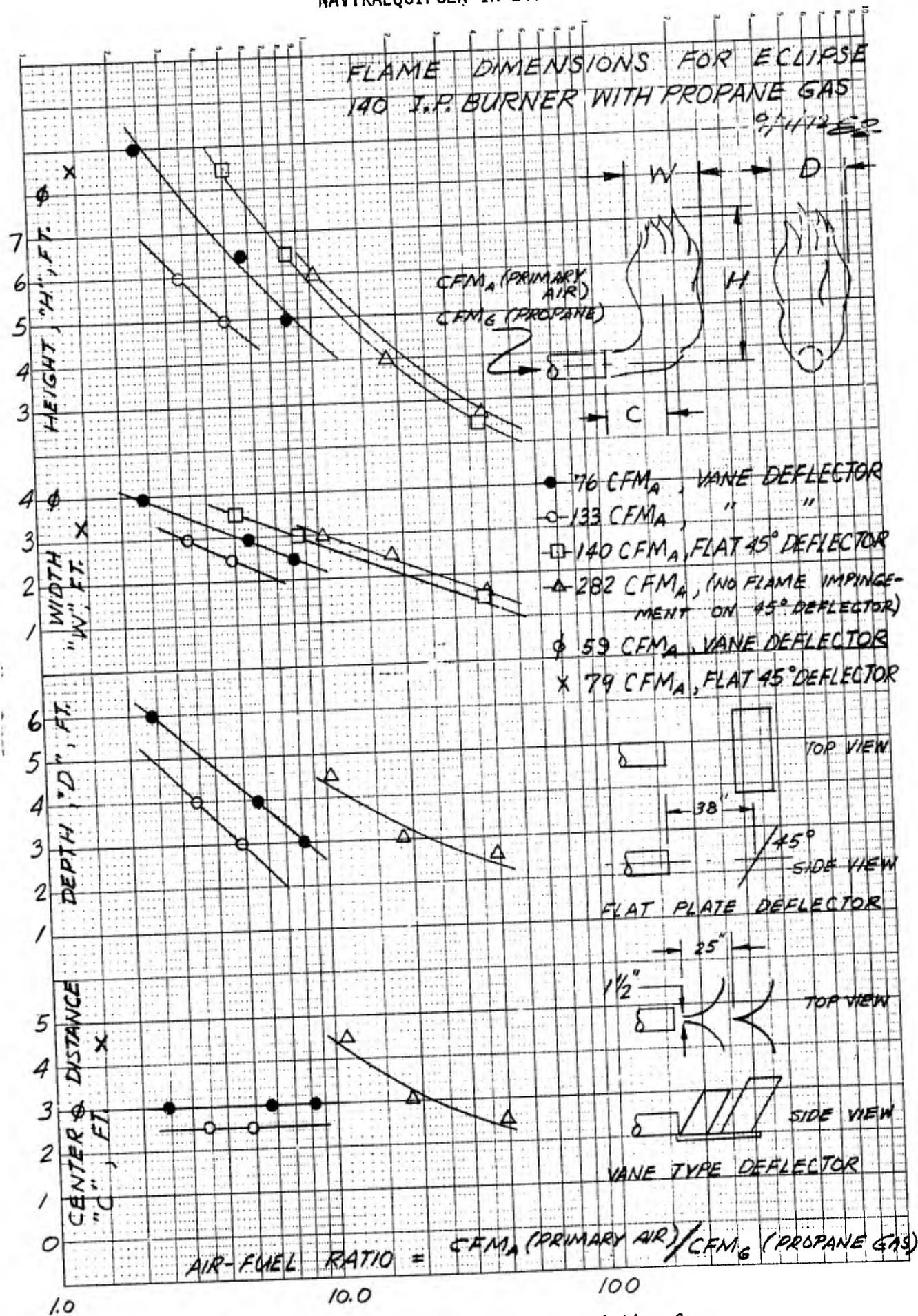


Figure 12. Flame Dimensional Characteristics for Eclipse 140 I.P. Burner with Propane Gas Fuel

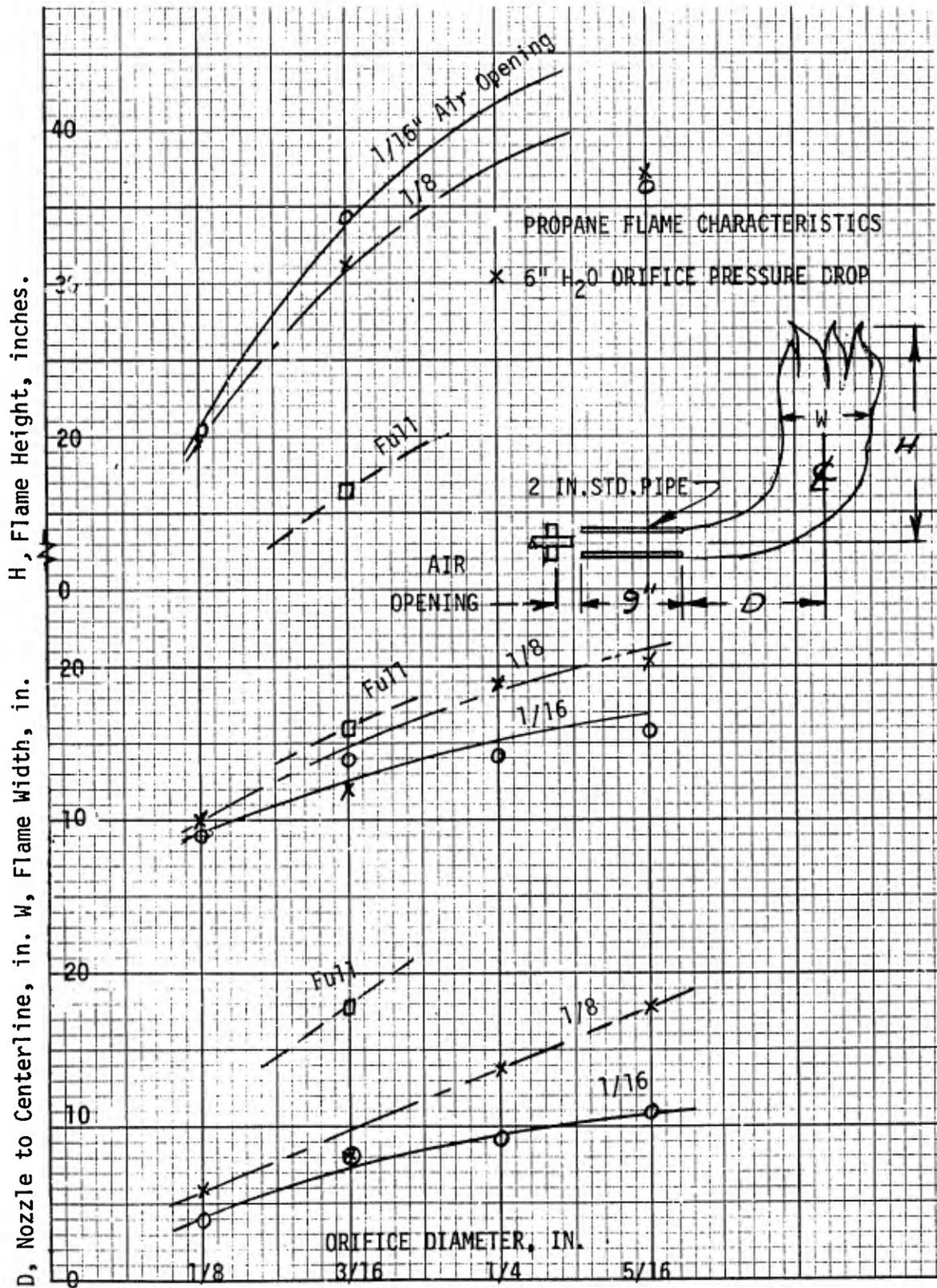
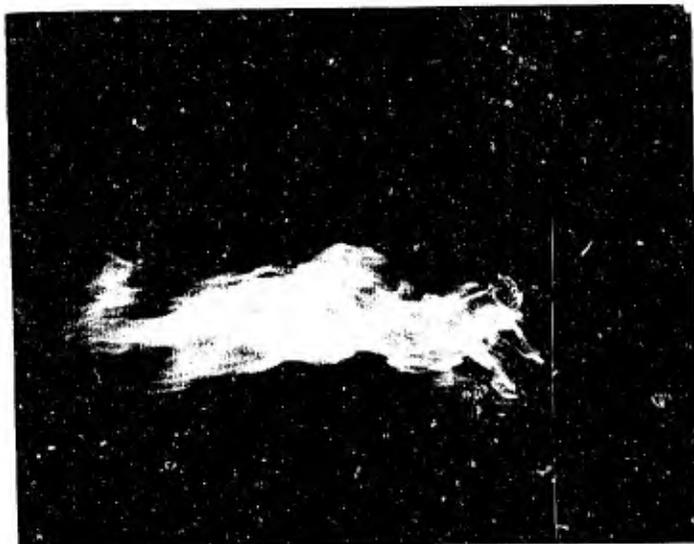


Figure 13. Flame Dimensional Characteristics for Aspirator Burner Nozzle



(c) Low air-fuel ratio



(b) Medium air-fuel ratio



(a) High air-fuel ratio

Figure 14. Propane Flame Characteristics

## STACK GAS MEASUREMENTS

As indicated in figures 15, 16, and 17, carbon monoxide (CO) measurements ranged from .001 percent to 0.1 percent for estimated normal fire fighting training conditions having sufficient primary and secondary air provisions. Increases beyond this range occurred for extreme low air-fuel ratio (low primary air) and/or small stack and draft openings (low secondary air). Increases in CO also occurred with applications of hose water as shown in figure 18. The CO readings for open air tests varied from about .0005 percent at the high air fuel ratios to about .01 percent at lower air fuel ratios. The results of parameter effects on Carbon Dioxide (CO<sub>2</sub>), Nitrogen Oxides (NO<sub>x</sub>) and Hydrocarbons (HC) measurements are shown in figures 19, 20, 21 and 22, respectively.

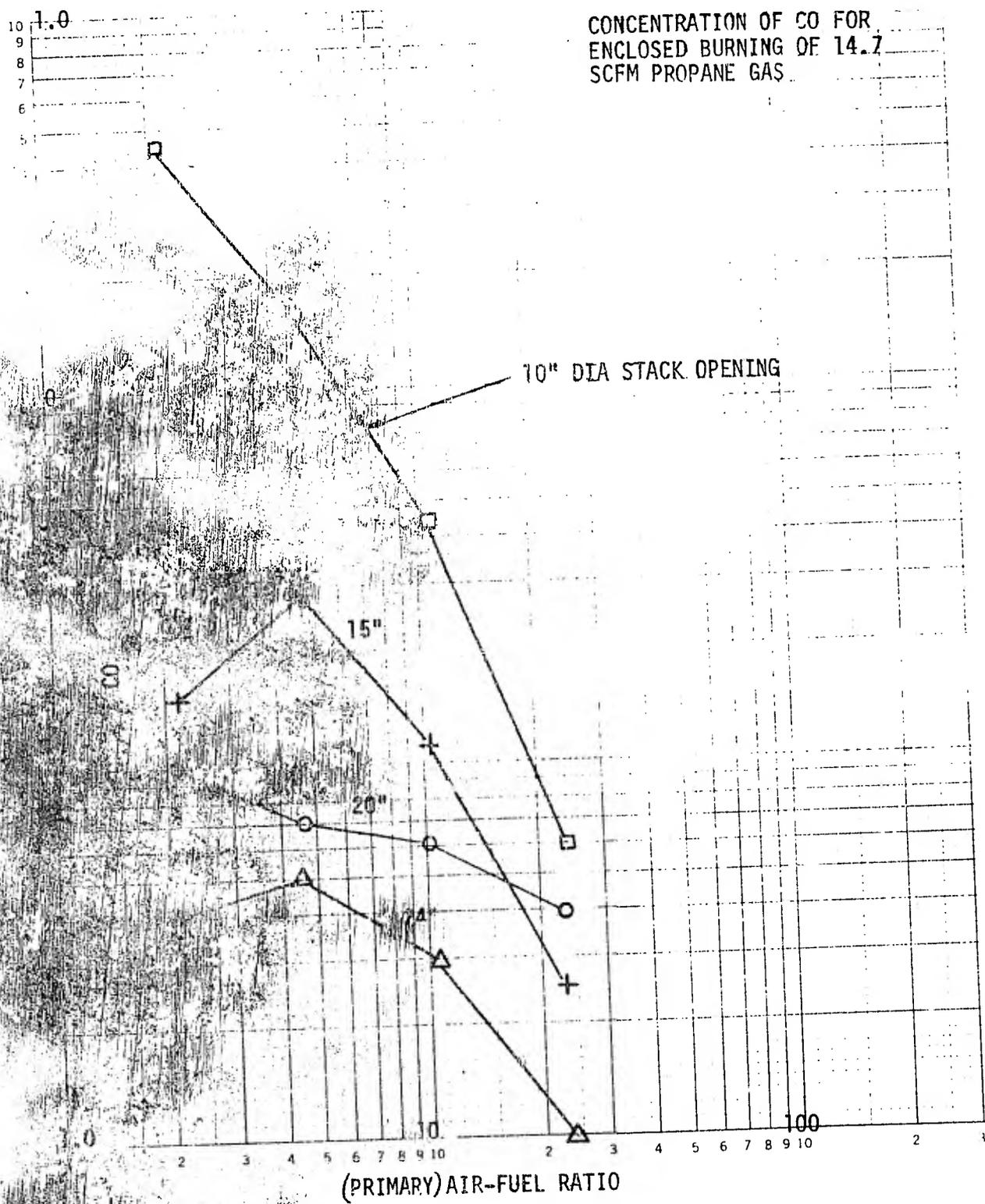


Figure 15. Concentration of CO for Enclosed Burning of 14.7 scfm Propane Gas

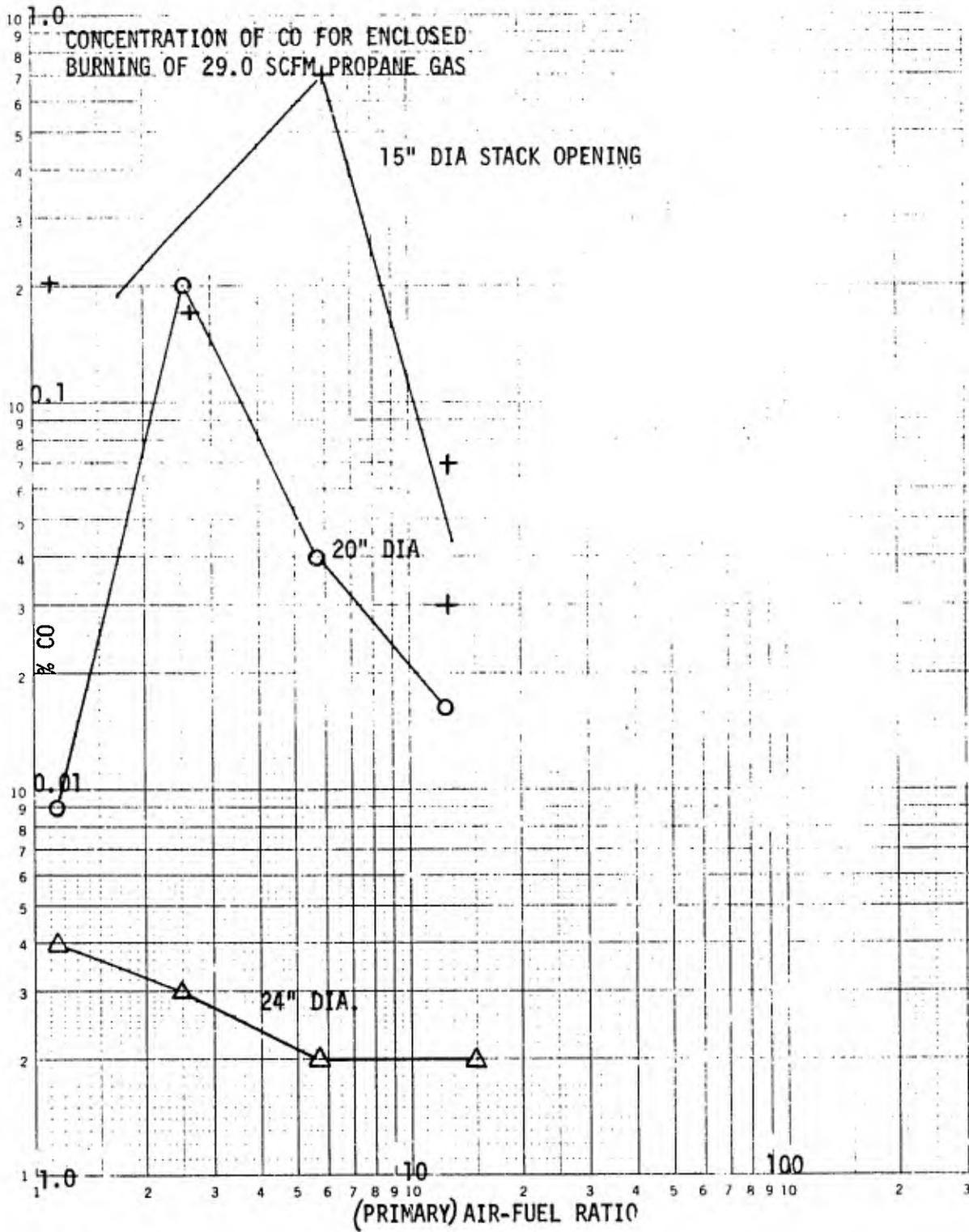


Figure 16a. Concentration of CO for Enclosed Burning of 29.0 scfm Propane Gas

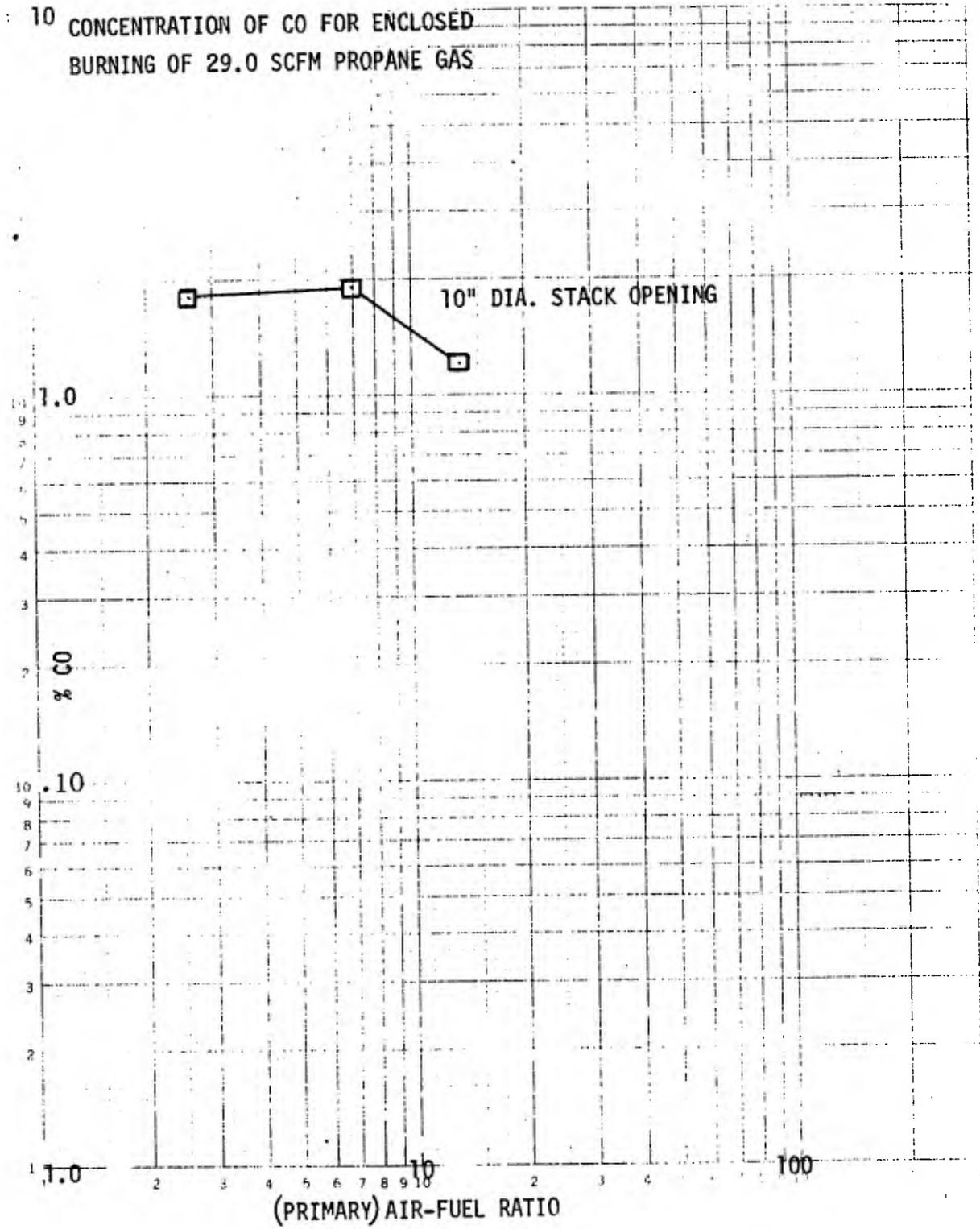


Figure 16b. Concentration of CO for Enclosed  
Burning of 29.0 scfm Propane Gas

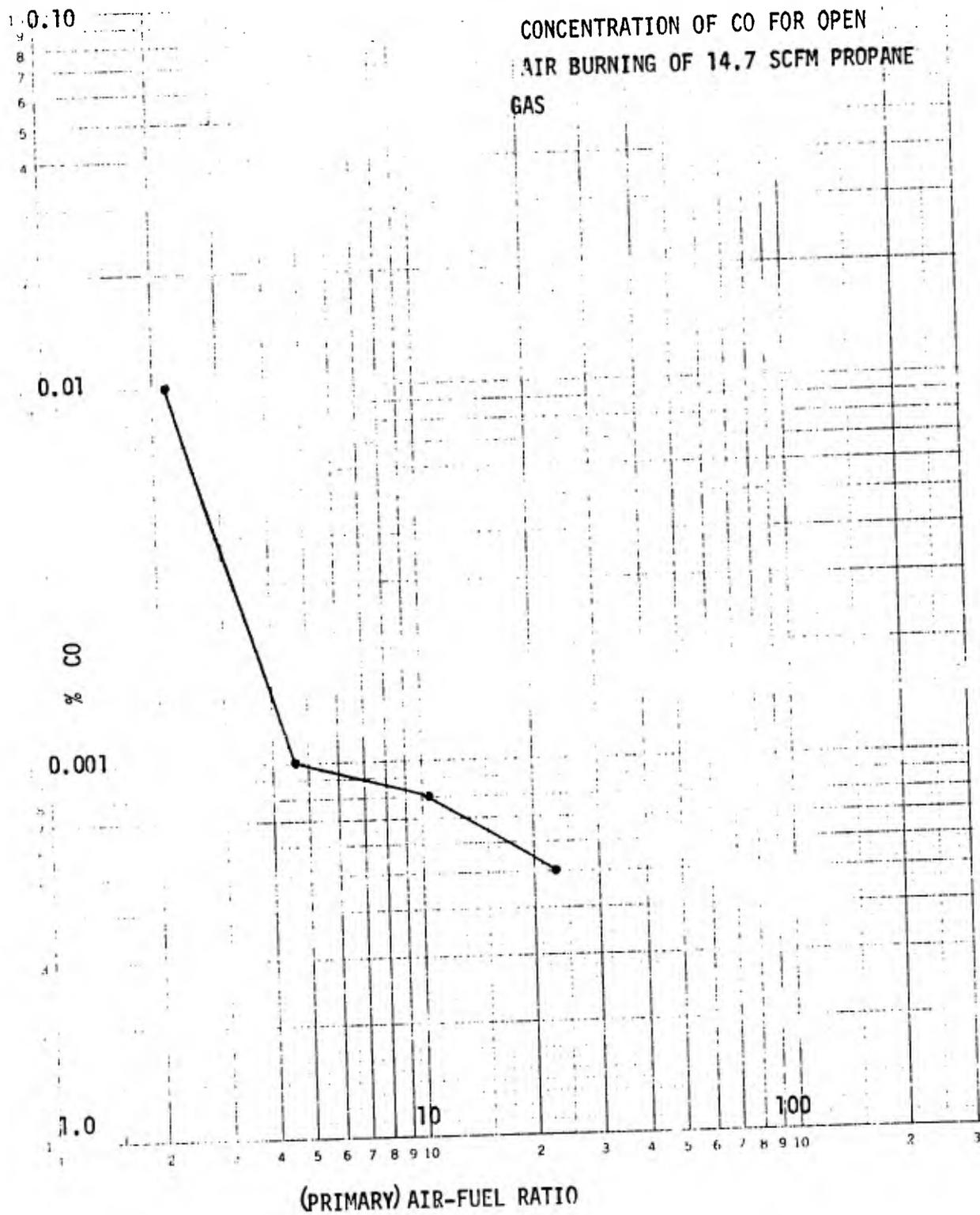


Figure 17. Concentration of CO for Open Air Burning of 14.7 scfm Propane Gas

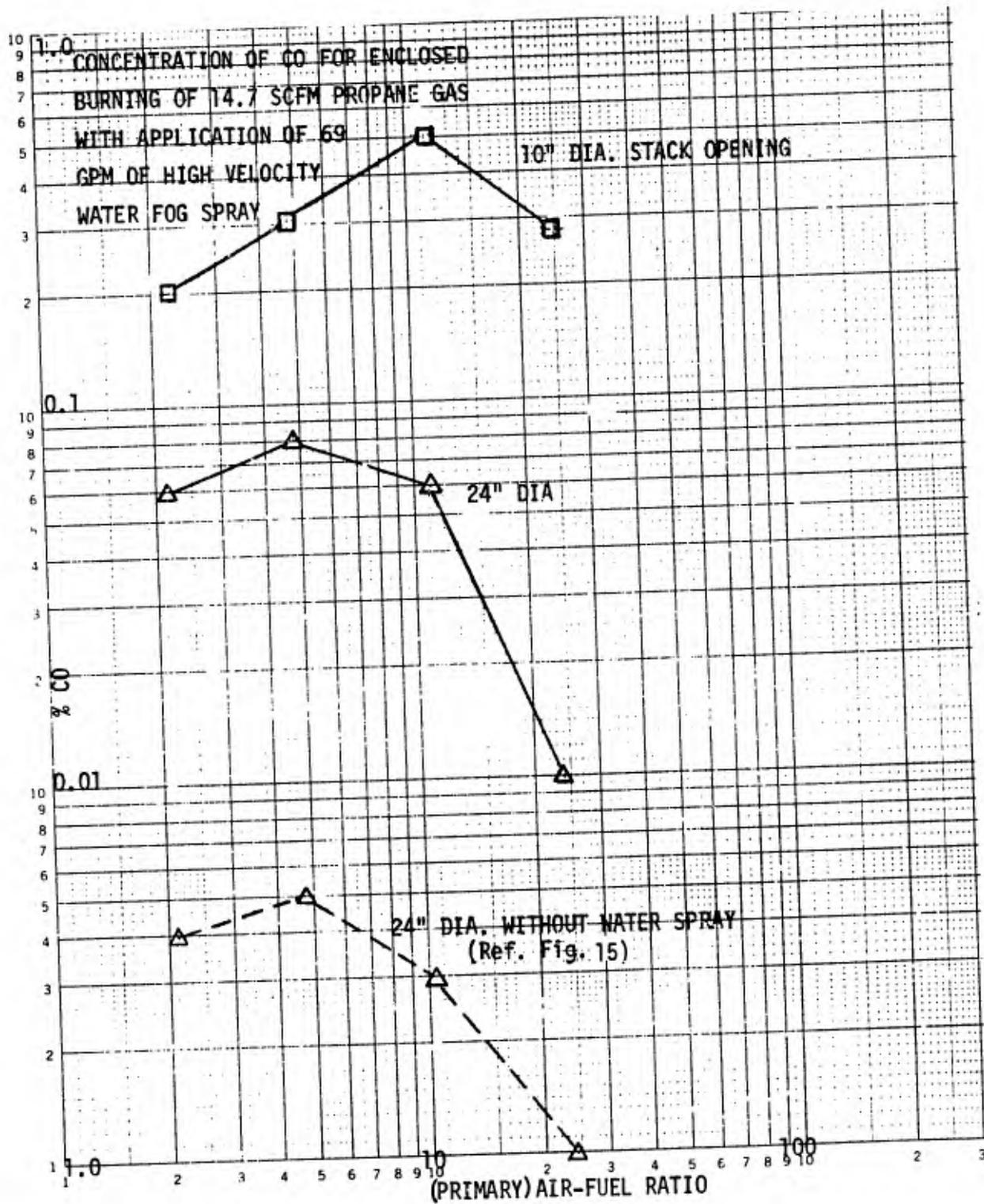


Figure 18. Concentration of CO for Enclosed Burning of Propane Gase with Application of Water Fog Spray

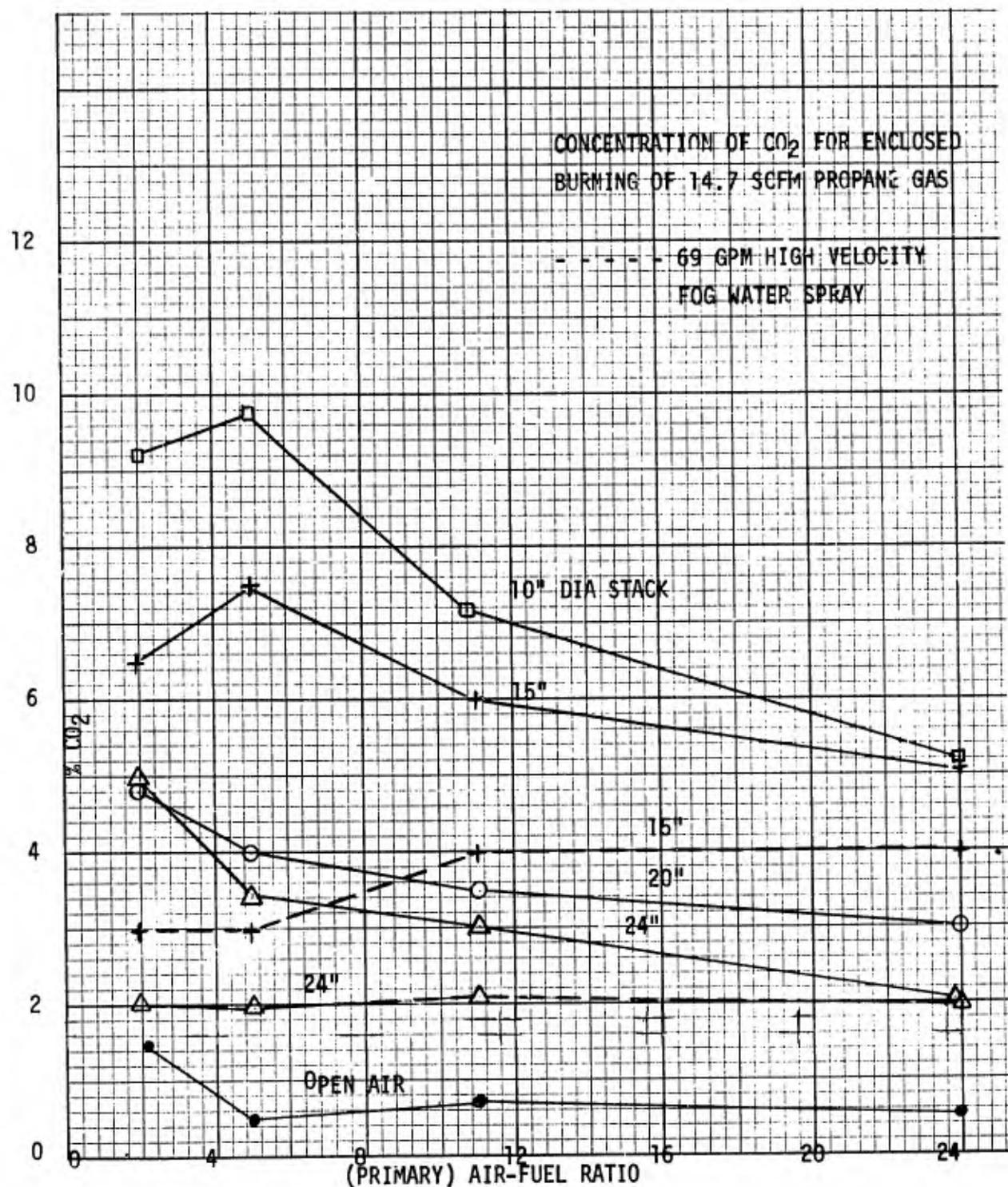


Figure 19. Concentration of CO<sub>2</sub> for Enclosed Burning of 14.7 scfm Propane Gas

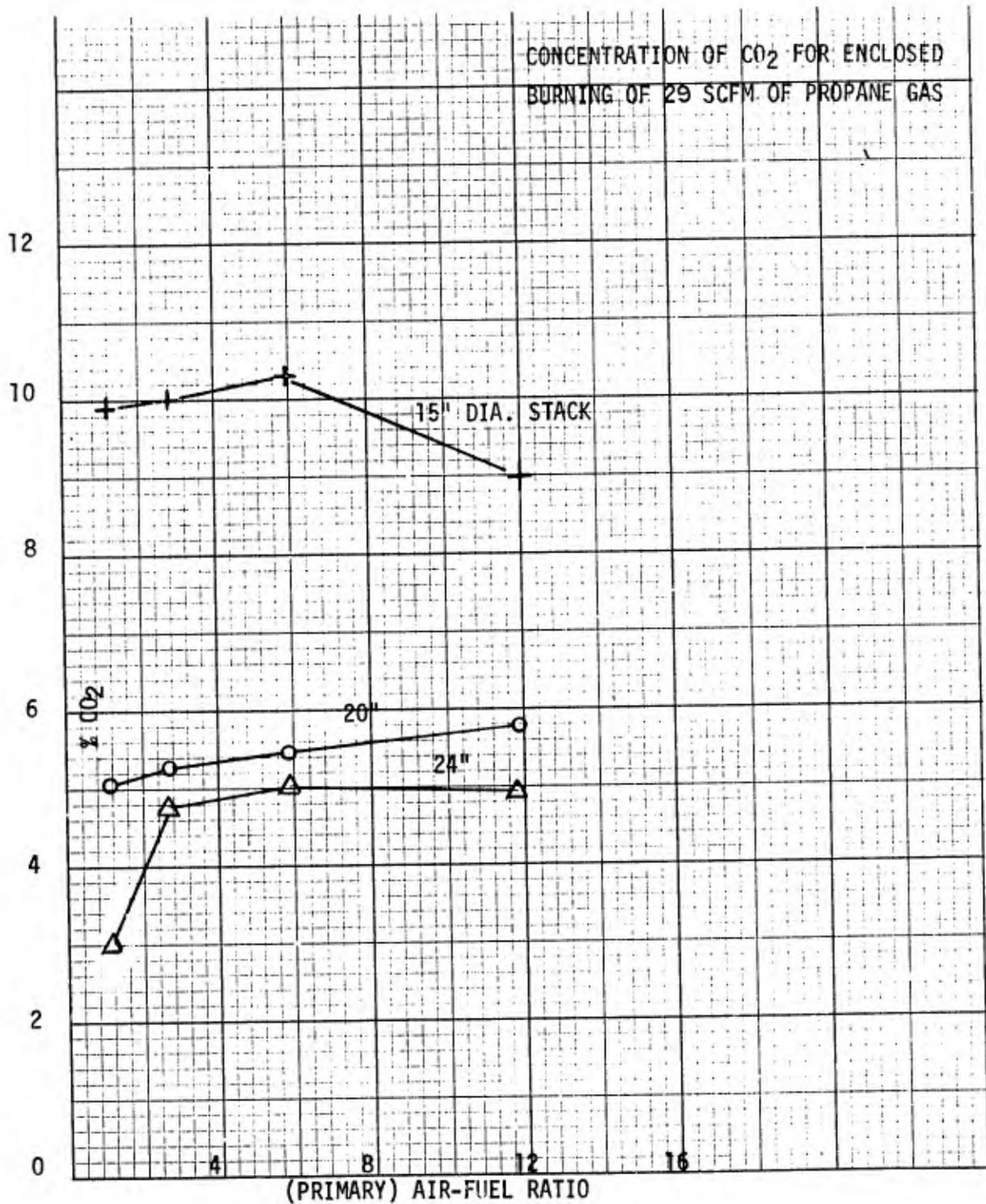


Figure 20. Concentration of CO<sub>2</sub> for Enclosed Burning of 29.0 scfm Propane Gas

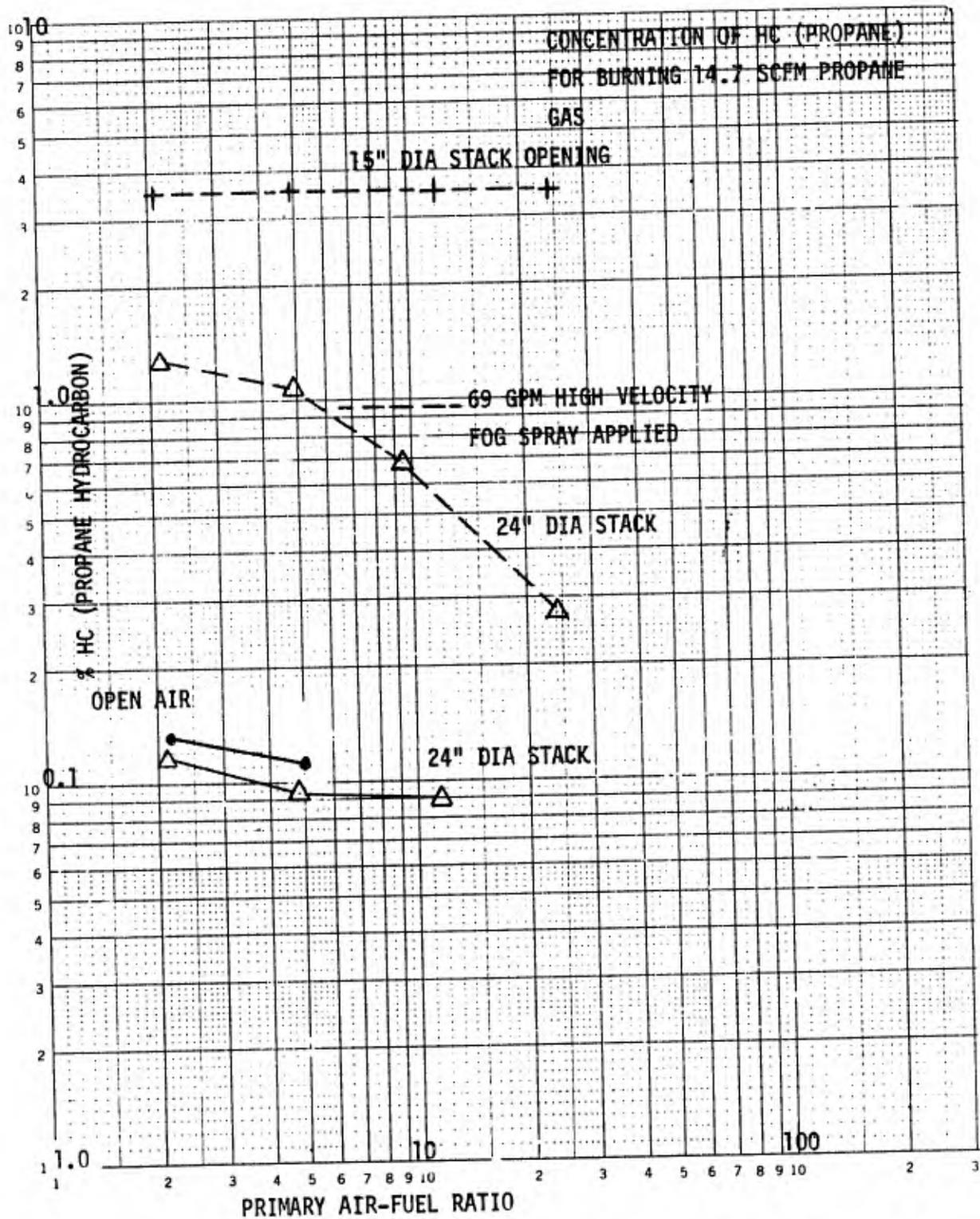


Figure 21. Concentration of HC (Propane)

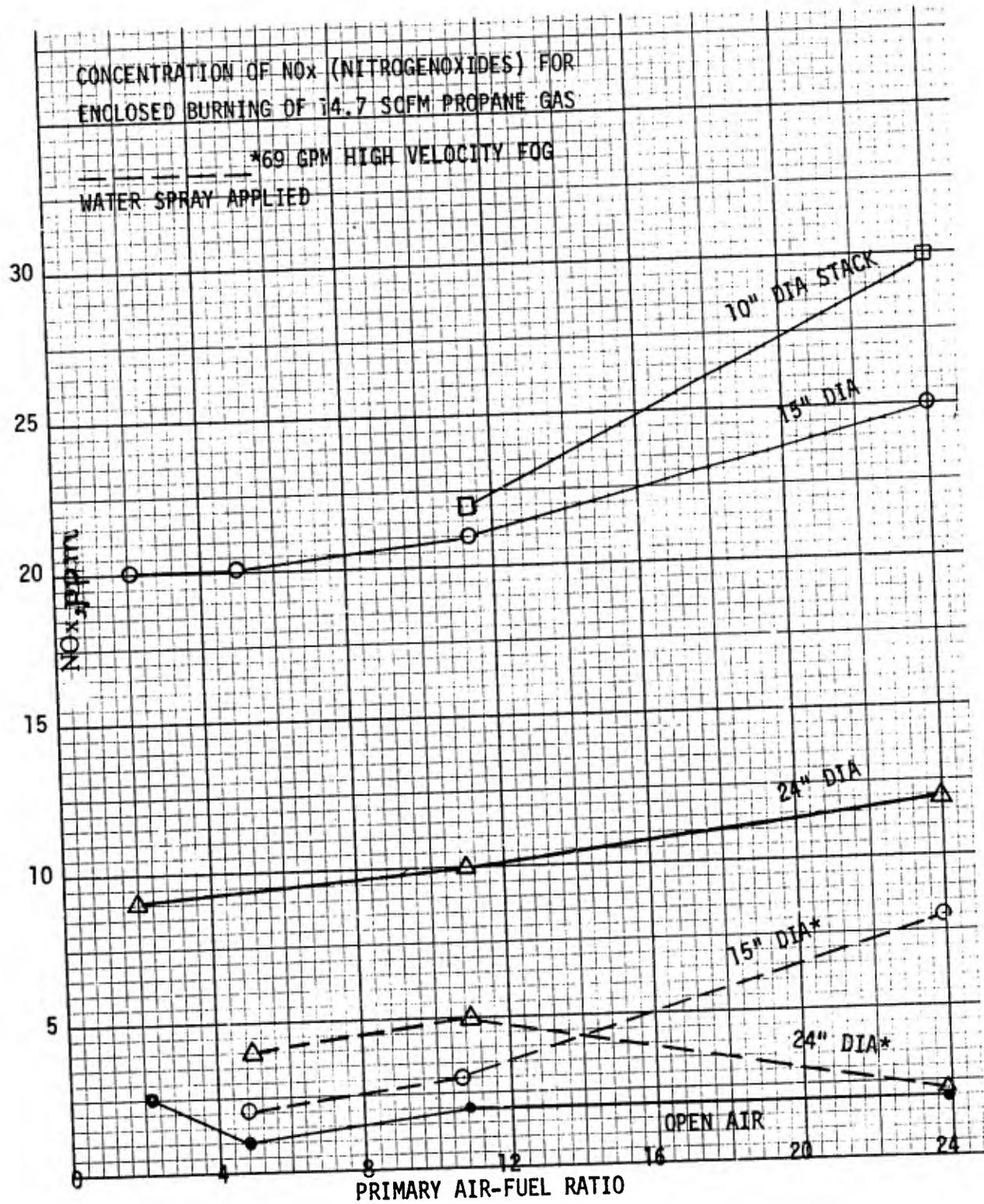


Figure 22. Concentration of NO<sub>x</sub> (Nitrogen Oxide) for Enclosed Burning of Propane Gas

## SECTION V

## DISCUSSION

## FLAME EXTINGUISHMENT AND REFLASH RESPONSE

A realistic simulation of flame extinguishment was demonstrated to be obtainable to the extent that pertinent flame characteristics were encountered. These may be considered primary sensory cues since the trainee would use them to determine his progress and make decisions. The following cues were noticeable during the various stages of extinguishment of the test equipment:

- Flame height was immediately reduced (with the gas valve still open) due to the initial cooling effect of the applied hose water spray.
- Flames were temporarily extinguished (gas valve closed) after applying a water spray for a predetermined time period.
- Reflash of burners occurred when application of the water was not of a sufficient quantity or duration to maintain a permanent extinguishment.
- Final extinguishment of a burner occurred after application of a sufficient predetermined quantity and for duration of hose water.
- Reignition of a previously extinguished burner by an adjacent lighted burner would occur unless water was reapplied to the extinguished burner and adjacent burners.

The realism produced by the above was particularly apparent by the initial natural cooling effect of the hose water and by the need to sweep the hose water back and forth across a flame area. The latter was necessary to maintain permanent extinguishment of previously extinguished burners and depended on various combinations of extinguishment and reflash rates from the digital control unit. For example, by appropriate settings of the controls, the difficulty of extinguishment could be selected. This would in turn require a corresponding increase in the sweeping rate of the hose water to complete an extinguishment.

The range of control settings were determined from estimated average extinguishment and reflash rates for existing diesel oil fire fighting trainers. Hence, the average extinguishment time for an 800 square foot engine room simulator would be about two to three minutes for three hose teams working simultaneously. This would require an estimated extinguishment delay of about 10 seconds maximum for each burner assuming a 4- by 4-foot area per burner and with no reflash during extinguishment. If the reflash clock rate in the digital control unit is increased, then the extinguishment clock rate would have to be correspondingly decreased in order to maintain the same total extinguishment time. A reflash spread across a diesel oil simulator was estimated to be about 30 seconds by

experienced fire fighting personnel. This would be consistent with data (\*) on flame spread across a hot oil fire indicating flame spread to about 750 feet per minute and would correspond to about a 0.5 second reflash time per burner.

#### DIGITAL CONTROL UNIT

Logic for a digital control unit was designed in a modular concept providing uniform characteristics for a large number of burners and simplified logistics support. The "A Module" was designed and fabricated to provide the extinguish features of immediate flame reduction when the sensor indicates water is being applied to that module, flame removal after one-half the selected extinguish time constant is reached, and a latching shutdown after water has been applied for the full time constant period thus preventing the burner from reigniting itself. The "B Module" provides the reflash feature of reigniting a shutdown "A Module" if its adjacent neighbor "A Module" has been burning for the reflash time constant period since water was last sensed as being applied at either burner.

These control characteristics were shown to demonstrate the primary features of a wide variety of fires and extinguishing materials. Special extinguishing chemicals with unusual features such as light water could be simulated with appropriate design of logic module characteristics. For example, light water tends to spread over the surface of the fire area to extinguish it. One method of simulating this would be to add a second interfacing module which would act in reverse to that of the reflash "B Module". Instead of spreading the fire by igniting adjacent "A Modules" it would extinguish adjacent modules thus simulating the spreading light water. Other unusual fire and extinguish features can be designed for simulation depending on training tasks required for a fire fighting trainer.

The digital control unit was designed to include many safety features which are critical to this dangerous environment being simulated. The power off or power loss condition will result in a positive shutdown of the burner electrical solenoid drive signals. High electrical noise immunity is provided in the logic type selected to avoid false startups of burners. A display unit was built to show continuous status of all burners to the operator. Dedicated special purpose logic control hardware for each burner was selected over an approach using computer control by time sharing each module's computation task in a control processor through a switching matrix with buffer stages. Any design changes must consider these safety features along with other more extensive monitor and control methods as required to protect against false burner starts which could be hazardous to human life.

#### FLAME CHARACTERISTICS

As shown in figure 12, the flame characteristics for the large burner were significantly affected by the quantity of fuel, air-fuel ratio and the flame deflector design. These effects are also indicated in figure 13 for the smaller burner used on the six-burner demonstrator. In general, the

\*See Reference 2, page 5 (pg 66).

flames were considerably larger and had a more natural flame action as air-fuel ratio was reduced. At air-fuel ratios below 10, the flames were fairly realistic and except for the lack of smoke, comparable to the free burning surface of a liquid fuel. Some slight evidence of smoke was noticeable at the extreme low air-fuel ratios. For the higher air-fuel ratios the flames were smaller and hotter with a steady "blow torch" effect as indicated in figure 14a which would be unsuitable for a training simulator.

Flame heights for diesel oil fires shown in figure 23 were determined from reference 2\*. To obtain similar flame heights from a gaseous fuel, the required modular spacing between gas burners must be considered. This would depend on the area coverage of a 70-100 gpm standard Navy fire hose (5) which produces a 6-foot to 8-foot diameter water fog spray. Using 6-foot as a maximum diagonal spacing between burners, this would result in an approximate 4-foot by 4-foot flame area. On this basis, from figure 12, for a single burner this height should be about six to seven feet. As indicated, this flame height can be obtained for various conditions of air-fuel ratio and the type of flame deflector. For example an air-fuel ratio of about 10 will provide a seven foot flame with the required flame area using a 45° flat deflector plate. However the vane type deflector will give similar flame dimensions for a three to four air-fuel ratio but with a more realistic flame action. Comparing flame heights on the basis of diesel oil fuel consumption and btu per hour heat content, the flame heights for an equivalent heat output for natural gas was determined to be approximately the same order of magnitude. It would remain to be seen, by large scale testing, whether flames from a group of burners merged together would produce larger flame heights than a single burner as analogous to the diesel oil fire in figure 23.

\*See Reference 2, page 5 (pg 66).

<sup>5</sup>Chapter 9930 Fire Fighting - Ship, Naval Ships Technical Manual, NAVSHIPS 0901-930-0003, Sep 1967 Edition.

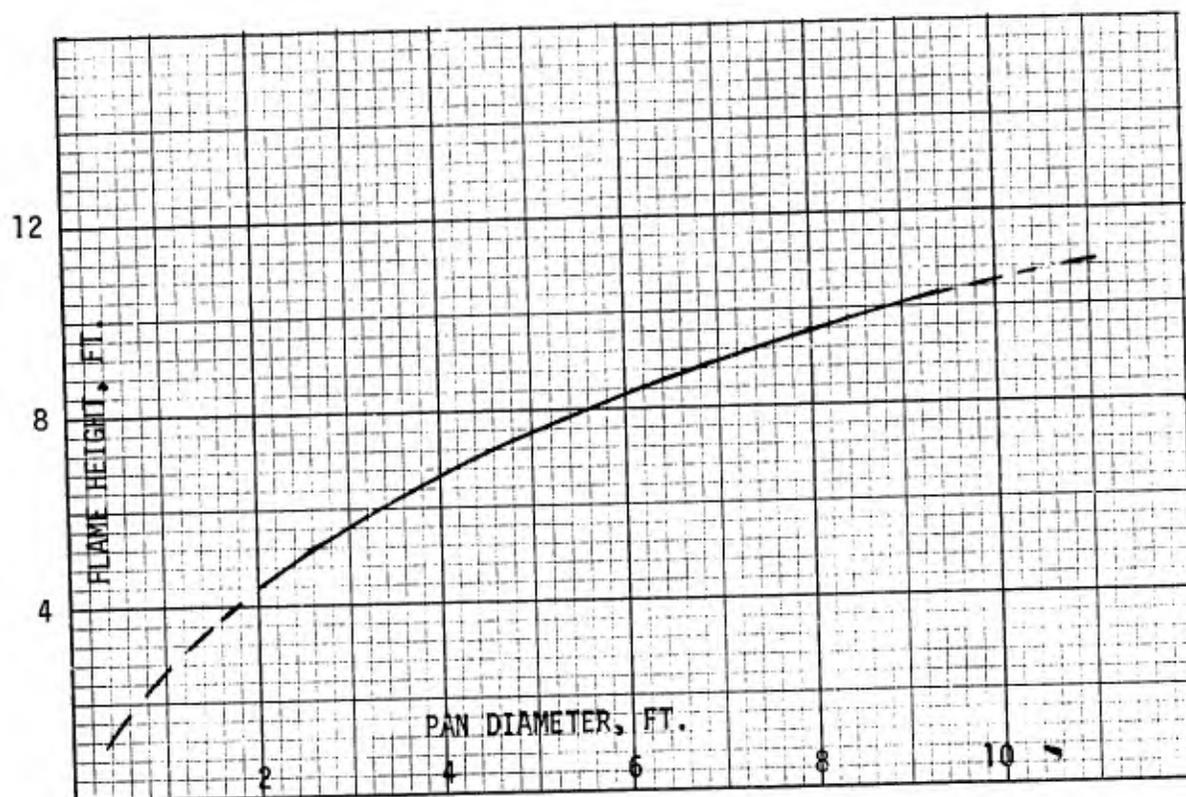


Figure 23. Flame Height for Diesel Oil Fire

## FUEL CONSUMPTION

Using the test data from figure 12, the amount of propane gas required will depend on flame height, air-fuel ratio and deflector design as follows:

<u>CFM PRIMARY AIR</u>	<u>FLAME HEIGHT</u>	<u>AIR-FUEL RATIO</u>	<u>scfm/ft<sup>2</sup> PROPANE</u>
75	6 ft	3.5	1.83
100	6 ft	4.7	1.77
140	6 ft	10	1.23
180 (extrapolated)	6 ft	12	1.00

The overall rate of gas consumption will also vary as the fire is being extinguished. Hence using a factor of 50 percent for this, and using a rate of 1.0 scfm/ft<sup>2</sup>, the total amount of propane gas for a 1,000 ft<sup>2</sup> area (engine room) for a 3.0 minute burning time is:

$$.50 \times \frac{.116\#/cu.ft. \times 1.0 \times 1,000 \times 3.0}{4.24\#/gal.} = 41.1 \text{ gals. per training session}$$

Since natural gas has a heating value of about 1,100 btu/scf compared with about 2,500 btu/scf for propane, a larger volume of natural gas will be required. Assuming that the amount of natural gas required is directly proportional to the heating value of the gas, then the required quantity of natural gas per training session would be

$$.50 \times \frac{2500}{1100} \times 1.0 \times 1000 \times 3.0 = 3410 \text{ scf}$$

The cost per training session would depend on contract bulk prices which are subject to drastic changes. At the present time, these are estimated at about \$9.25 for propane training session and about \$3.37 using natural gas. Comparisons with a diesel oil training fire are difficult due to many variables involved. These would include the type of students, length of burning time, the size of trainer, wind conditions, oil salvage, etc. Assuming identical conditions for size and duration as above, a diesel oil fire would require about 15 gallons of fuel oil and 4.5 gallons of gasoline or an estimated cost of about \$5.60 per training session.

#### STACK GAS ANALYSIS

The test data indicate the general sensitivity of the emissions to the test equipment design and the test parameters. The generation of CO was especially sensitive to the heat transfer from the flames during initial tests. This was due primarily to the relatively high ratio of the flame enclosure surface to the enclosed volume and the use of a water spray on the outside surface to protect the structure from the intense heat. In order to obtain meaningful data on the emissions due to other parameters, it became necessary to offset the dominating effect of the heat transfer from the flames to the immediate surroundings. Hence the chamber interior was insulated to obtain a heat transfer condition comparable to a full sized fire fighting trainer. The effect of heat transfer on combustion in flames is noted in literature (6-7) which indicates the complexity of the flame mechanism particularly for fuel-rich flames. However, the basic theory explains qualitatively the dramatic reductions in CO and HC with increasing primary and secondary air provisions. For example propane is decomposed in the initial phase of the flame to form CO but its chemical bond energy is relatively high. Hence high flame temperature and sufficient oxygen is required to decrease the CO concentration. The conversion of CO to CO<sub>2</sub> is enhanced by longer residence time since this is a relatively slow reaction compared with CO formation.

<sup>6</sup> Fristrom, R.M., The Mechanism of Combustion in Flames, Chemical and Engineering News, Oct 1963.

<sup>7</sup> National Air Pollution Control Administration Publication No. AP-65, Control Techniques for CO Emissions from Stationary Sources, U. S. Department of Health, Education and Welfare, Mar 1970.

As previously mentioned, during initial testing a considerable amount of heat was being absorbed from the flames by the surrounding uninsulated enclosure. This resulted in relatively high initial CO gas measurements ranging from 1 percent to 6 percent. Subsequent insulation of the chamber provided a means for attaining levels of CO within the acceptable range for fire fighting training (8). After minimizing the heat transfer, it was evident that the variation of the CO level, within the acceptable range, was sensitive to the primary and secondary air parameters as well as loss-water effects.

The effect of increasing secondary air on CO reduction by increasing the stack exhaust opening is shown in figures 15 and 16. These indicate a CO reduction of two orders of magnitude from .45 percent for a 10 inch diameter stack opening to about .005 percent by increasing the stack diameter to 24 inches. Maximum CO values occurred as the air-fuel ratio was decreased from a high of 4:1 to about 4:1. Further reduction of an air-fuel ratio to extreme low values resulted in a decrease in CO from the maximum value as the burning rate less complete.

CO occurred when 69 gpm of high velocity fog water was applied to the flames as shown in figure 19. Since these measurements were made under steady state conditions with a continuous flame, they will tend to be higher than actual training conditions. In an actual training situation the fire would be extinguished by valve closure and the increase in CO due to the applied water would be momentary. Nevertheless, CO readings for the 24-inch stack exhaust diameter were still better than the acceptable safe limit. A reduction in secondary air with a 10-inch diameter resulted in an increase in CO between .20 percent to .5 percent with the hose water. On the basis of an acceptable CO level for the 24-inch diameter exit opening a ratio of stack area to surface flame area of about .1 minimum would be necessary.

Nitrogen oxide (NOx), as with CO, requires careful consideration from a toxicity standpoint. The TVL (threshold value limit) (9) for NOx is 5 ppm compared with 50 ppm for CO. The acceptable limit for NOx for a short time (10 minutes) fire fighting training situation would be about 30 ppm. The NOx readings as shown in figure 10 ranged from 1 ppm for the open air tests to about a maximum of 10 ppm for the combined extremes of high air-fuel ratio and low secondary air provisions. It is apparent that the cooling effect of increasing the secondary air reduces NOx while increasing air-fuel ratio tends to raise the flame temperature and subsequently the NOx. This trend

<sup>8</sup> Memorandum, BUMED-7321-DAM:jbw, 26 Sep 1973, Information on Carbon Monoxide Inhalation Effects; reply to request to, Bureau of Medicine and Surgery.

<sup>9</sup> Sax, N. Dangerous Properties of Industrial Materials, page 3, 2nd ed. 1963.

appears to be in accordance with literature (10) citing the increase of NO with flame temperature. It is also noted that NO<sub>x</sub> is reduced considerably when hose water is applied to the flames.

Increases in HC (propane) and carbon particles (smoke) were evident for the simultaneous reduction in secondary air with the extreme low air-fuel ratios. These increases probably replace the formation of some CO in the flame process and hence would account for the reduction in CO for extreme low air-fuel ratio mentioned previously. However, as cited in literature (7), the fuel rich burning flame is a complex process which is as yet not completely understood.

The HC detector tubes used for test measurements were not direct readings as were the detector tubes for the other gases, and were found to be a relatively long time-consuming process. For this reason the readings shown in figure 23 are most probably conservative in tending to give higher readings than the actual case. However, HC, like methane, is considered an asphyxiant and only dangerous when preventing sufficient quantities of oxygen to be available. These generally have a TVL of about 1,000 ppm. (This is unlike hydrocarbons from a fuel such as JP-5 which has tentative emergency levels of about 5 mg/liter for 10 minutes.) On this basis, the percent HC as indicated in these tests should not present any problem for fire fighting training.

The measurements of CO<sub>2</sub> shown in figures 20 and 21 indicate excess air conditions. Also, the concentration of CO<sub>2</sub> decreased as the primary and secondary air was increased. This is to be expected since theoretically the CO<sub>2</sub> readings would decrease in proportion to the amount of excess air beyond the stoichometric burning at 16 percent CO<sub>2</sub>. Since the CO<sub>2</sub> levels did not appear to vary significantly with the air-fuel ratio it would indicate that the control of the percentage of CO<sub>2</sub> and O<sub>2</sub> would depend primarily on the exhaust opening effects on secondary air. It was noted that levels of CO<sub>2</sub> less than 3.5 percent with O<sub>2</sub> levels greater than 15 percent were obtained with a 24-inch diameter stack opening. As expected, the O<sub>2</sub> levels were reduced to about 10 percent or less for smaller stack openings approaching 10-inch diameter.

#### BURNER AND SENSOR SYSTEMS

The horizontal side-mounted burner arrangement was chosen to locate the burner controls outside the flame area and to minimize problems of inadvertent pilot light extinguishment when hose water is applied. Also flames would be

<sup>10</sup> Crynes, B.L., and Maddox, R.N., Status of NO<sub>x</sub> Control from Combustion Sources, Chemical Technology, Aug 1971.

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positioned by locating the horizontal burner nozzle within a section of a proposed trainer with the flame exiting from the nozzle and turning vertically upward due to the bouyant forces of the burning gases.

Various diameter tubular nozzles were initially experimented with aspirator type of air supply for the six-burner demonstrator. These tended to produce a flame flashback between the gas orifice and air supply inlet air. This was due to the flow resistance of a constant cross sectional area of the nozzle and/or the lack of forced air (blower) supply. A flat divergent nozzle operated successfully without forced air for the six-burner unit. A 600 cfm blower was supplied with the larger burner unit although, as indicated in figure 12, forced air rates considerably less than this were used for the flame and stack gas tests. This would indicate that for a multiple array of burner units, the individual blowers for each burner could be replaced with a piping manifold as a design trade-off.

The tests for flame characteristics shown in figure 12 were made with a 10-inch diameter tubular nozzle 12 inches in length. Additional tests were made with a stainless steel sheet metal burner nozzle with an extended length, as shown in figures 24 and 25. Test results with a 6-foot and 10-foot length indicated a somewhat reduced flame height with nozzle length. Nozzle surface temperatures tended to increase with the nozzle length up to about a reasonable 800°F. Hence, this appears to be a feasible method for providing flames to the interior of a fire fighting trainer with burners and controls located outside the flame area.

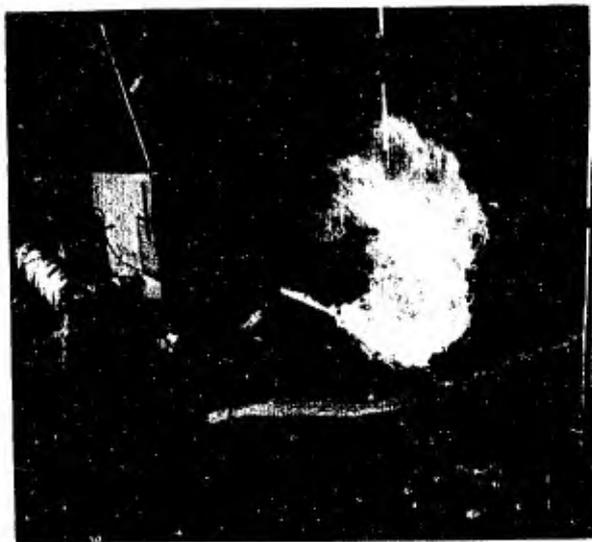


Figure 24. Burner With Six-Foot Nozzle Extension

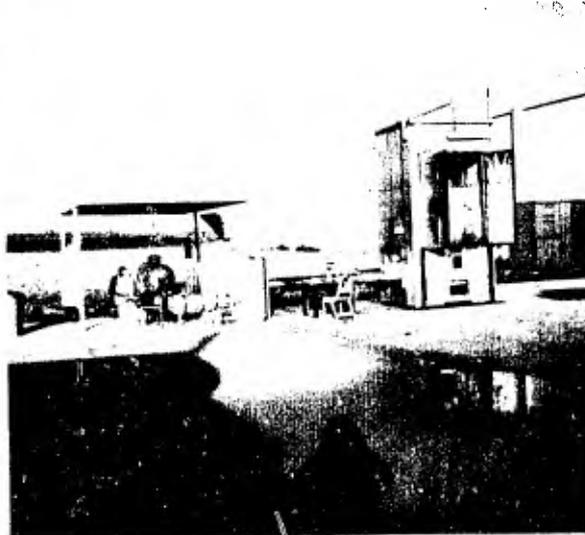


Figure 25. Burner with 10" X 10' Nozzle Extension

Flame deflectors at the end of the burner nozzle as shown in figures 26 and 27 provided a more efficient flame distribution. The individual flame area of a burner was approximately doubled using an appropriate deflector although flame heights were correspondingly reduced. In the case of the full size burner, vane deflectors were used which consisted of forward and rear sections of curved surface made from stainless steel sheets. These were slanted so that the flames were deflected upward and outward simultaneously. The two forward sections nearest the nozzle were separated by a 1-1/2 inch gap. This permitted division of the burning gas into separate areas which merged together as the flame rose upward resulting in a wider flame area. As indicated in figure 12 the centerline distance of the vertical flame from the end of the nozzle varied somewhat when no flame deflector was used.

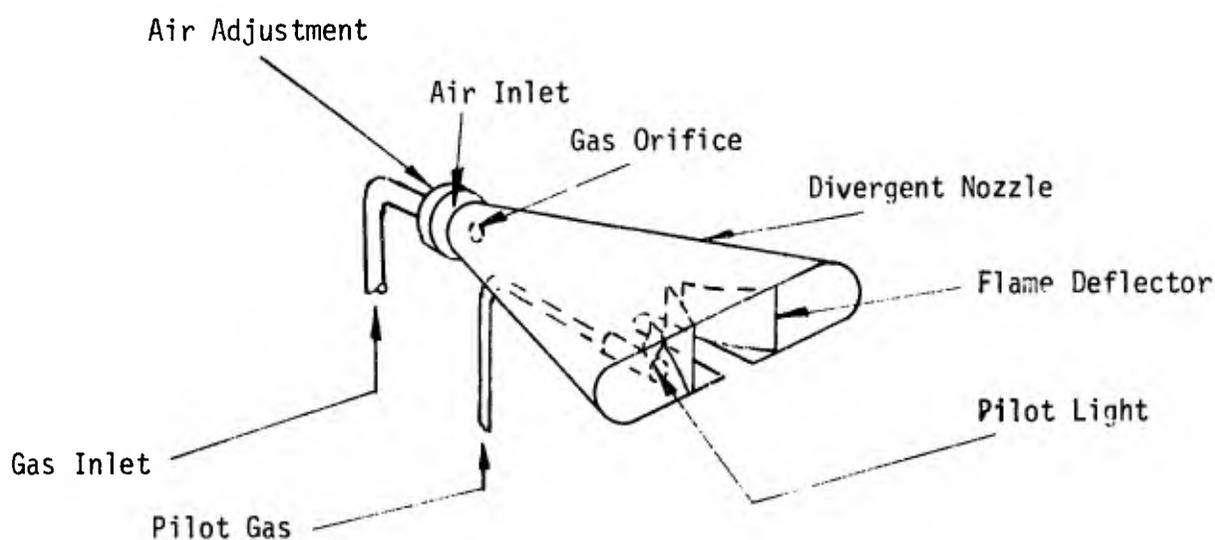


Figure 26. Nozzle and Deflector for Six-Burner Unit

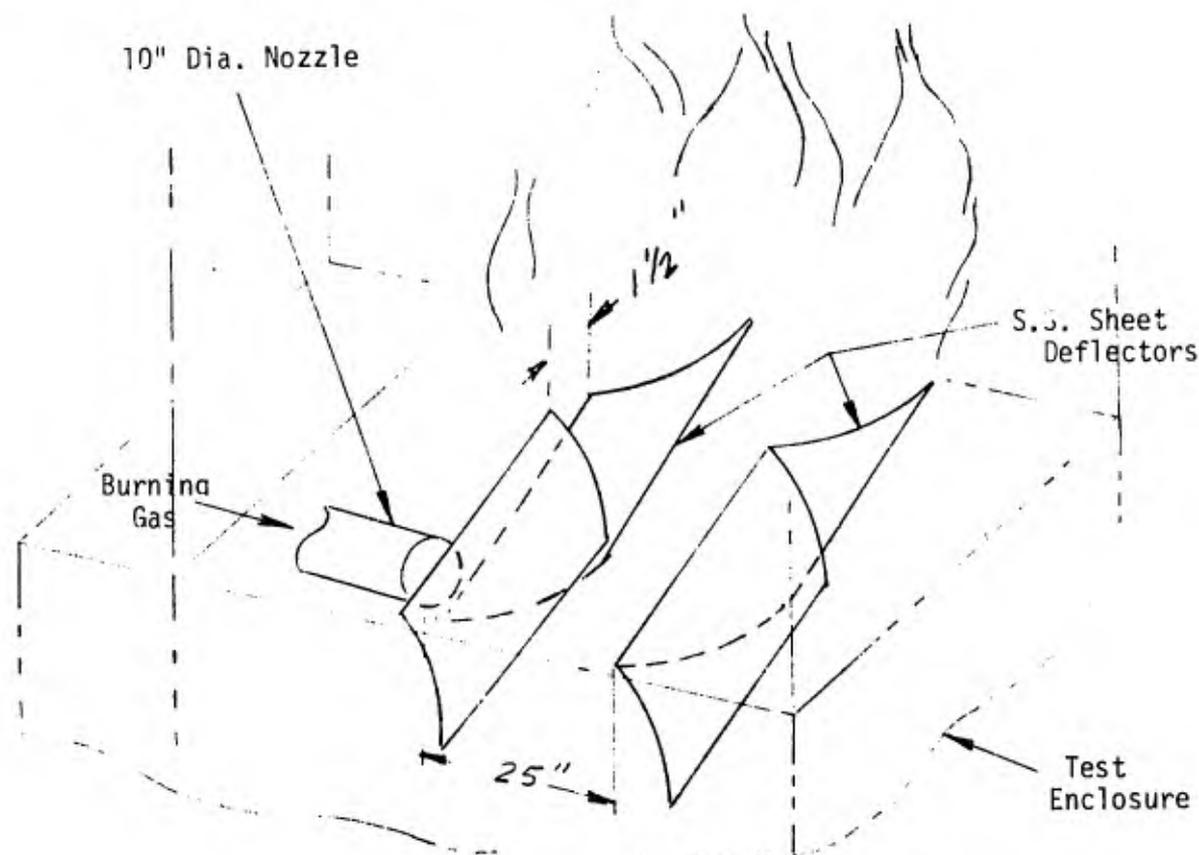


Figure 27. Deflector for Full Size Burner Unit

The pilot lights provided repeated ignition of the six-burner unit as the solenoid valves were actuated. The pilot lights also maintained gas supply to the individual burners through a safety valve. Hose water spray on occasions would inadvertently enter the burner nozzle near the pilot light and cool the thermocouple causing it to shut off the gas supply. This problem was avoided to large extent by installing a protective baffle over the thermocouple resulting in less frequent shut down of the safety valves. Although this did not occur frequently enough to disrupt the operation of the unit, this type of pilot light sensor would not be recommended for a final configuration. In lieu of the thermocouple an ultraviolet light sensor similar to that used on the single burner demonstrator would be recommended.

The magnetic float and reed switch type water sensor was adequate for demonstrating system operation. However, the disadvantages of this type of sensor were apparent. Time lags affecting system response to the hose water were noticeable particularly when a fast reflash time constant was set on the control unit. This was due to the time required for the water level in the float chamber to recede and deactivate the float switch. This time lag was aggravated by the decrease in flow out the level control orifice as the water level receded. A meniscus effect was also evident at the orifice as the water level stabilized which effected time lag and float level position. Also a cleanup maintenance problem was significant due to dirt and scale being washed into the float container by the hose water. For

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these reasons this type of sensor would not be a final recommendation. More responsive type sensors which would eliminate the need for a float chamber are still under consideration. These include a rotary vane and probe type flow meter with no moving parts. Investigations (13) are currently underway for methods of detecting foam which would include ultraviolet (UV) sensors.

### GENERAL COMMENTS ON SIMULATION REQUIREMENTS

The question arises whether the previously mentioned sensory cues are sufficient for an accurate simulation of a natural fire. For example, the extinguishment of an enclosed (engine room, boiler room, etc.) diesel oil fire involves various hose-handling maneuvers, including horizontal or vertical hose nozzle positions.

Before a trainee enters an enclosed simulator, hose water would be sprayed through the door opening with the hose in a horizontal position. The purpose here would be to cool the flames and create a partial vacuum thereby preventing flames from coming out the door so entry can be made. A similar cooling effect and flame height reduction (to about 30 percent of initial height) was observed with the gas burning equipment. Upon removal of the hose water, and with the gas valve still open, the flames would regain their initial height. This would occur since the gas and air were pre-mixed before combustion and hence an artificial means of sensing the applied water would be required to initiate and maintain extinguishment. Initially, two-stage gas valves were used (in the six-burner demonstrator) with the first stage activated to simulate the initial flame height reduction. These were later re-wired for single stage operation since no appreciable differences in flame response were apparent due to the natural cooling effect of the water spray. Although realism of this initial phase of extinguishment appeared promising with the available small scale test equipment, these results cannot be considered fully conclusive until tests can be made with full scale equipment and comparisons made with a large size diesel oil fire.

A subsequent hose handling maneuver is required after the trainee enters the doorway. In this case, he may be instructed to partially enter the doorway with the hose lifted high and "goosenecked" so that the nozzle is pointed vertically downward. The hose nozzle is then maintained about waist high and the hose water swept over the flames adjacent to the wall near the door. This extinguishes the flames and tends to prevent reflash after complete entry is made into the trainer. Simulation would be obtained from the extinguishment and reflash performance characteristics discussed earlier. The extinguishment and reflash time constants could be selected from a range of settings on a control console to provide the required degree of difficulty of extinguishment. For a realistic trainer, it would be necessary to determine optimum burner size, number of burners and matrix spacing of extinguishment sensors for the localized area near the door. This would require some comparative type tests of a full size gas burner array with a diesel oil fire. Realism would be accomplished by the extinguishment response of the burners and the need for a sweeping action of the hose water to avoid reflash and re-ignition by adjacent burners.

<sup>11</sup> NAVTRAEQUIPCEN Research Task No. 5715.

The final hose maneuver, when the trainee has successfully entered the trainer, is to point the hose at the rest of the fire with the hose held horizontal about two feet from the deck. A sweeping action of the hose is still required as the fire is "worked" into a corner or against a bulkhead. The simulation of this final phase of extinguishment with a synthetic array of burners would depend essentially on the quantity, duration and area of coverage by the applied water in relation to the matrix size of water sensors.

#### LIMITATIONS OF SIMULATION EQUIPMENT

Probably the most important limitation is the size of the demonstration and test equipment. As mentioned previously, a much larger, full size equipment would be required to verify the accuracy of the proposed simulated flame extinguishment requirements. Another important limitation is the lack of capability for using extinguishing agents other than water. Since the objective was to demonstrate feasibility of simulating realistic type flames and logic controlled extinguishment response a detailed investigation of foam sensors was postponed for later study (12). However, it is recognized that foam application is a primary means of fighting fires aboard ships and is being used more frequently in fire fighting training. Hence, it would be unrealistic to exclude this capability in any future synthetic fire fighting trainer. This would require the development of sensors to detect both foam and water. To incorporate this feature and as a follow-on to this report, efforts are under way (12) to investigate UV sensors as a possible method for detecting foam.

It is also noted that the previously mentioned simulation requirements would not include certain possible characteristics of a diesel oil fire. For example, the inadvertent holding of the hose nozzle too close to an oil fire surface could cause a "digging" or oil splattering type of effect. Discussions of this possibility with experienced fire fighting instructor personnel, however, indicate that this would not be a serious simulation omission. This is because a detrimental type of "digging" occurs mainly with use of a solid stream of hose water which is not permissible with an oil fire. Although it is possible to obtain some sort of digging action from a high velocity fog nozzle, the nozzle would have to be held deliberately within a few inches of the oil surface. Even this would not cause any detrimental oil splashes unless possibly the oil fire is exceptionally hotter than is normally used for training. For these reasons, it would appear that a "digging" type of extinguishment response would not be considered a necessary requirement.

Also not included for simulation would be the movement of masses of burning oil which are floated away during application of hose water. This characteristic is not considered as a means for controlling a diesel oil fire, rather, it is the "working" of the fire by sweeping the hose water over the fire to accomplish rapid extinguishment that is the main objective. Moreover, it would appear that any noticeable floating away of a burning mass of oil may be somewhat similar to the removal of flames from burning area by extinguishing gas burners. Again, it would be necessary to verify these contentions by appropriate larger scale tests.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

FEASIBILITY

The system concept of a logic controlled non-pollutant fire fighting trainer responding to hose water application was demonstrated as feasible.

Realism was apparent from the natural flame response and the controlled extinguishment and reflash cues provided by the digital control unit. These cues appeared to be sufficient in view of the relatively short training sessions and the need to maneuver the fire hose as in a diesel oil trainer. Verification of training simulation on a larger full size scale would be recommended. Further studies for application of foam and other extinguishing agents are still required.

STACK GAS ANALYSIS

The use of propane or similar gaseous fuels could be used as an acceptable fuel for fire fighting simulation. Natural gas being less expensive would be recommended in lieu of propane. A safe toxic level was obtainable using a gaseous fuel (propane) if adequate primary air (air-fuel ratio) and secondary air (stack and bottom draft) are provided.

The generation of carbon monoxide is particularly sensitive to parameters of air-fuel ratio, stack and bottom draft openings, provided that the dominating effect of heat transfer cooling of the flames is minimized.

An air-fuel ratio between 4.0 and 12.0 could be used for nontoxic and realistic flames. The stack exhaust and inlet openings should be a minimum of 10 percent of the flame area for adequate secondary air, although this should be verified on a larger full scale test.

ADVANTAGES

In addition to the clean burning capabilities of the fuels other potential advantages were apparent as follows:

- Safe toxic levels were obtainable with few gases given off as compared with the many gases, pollutants and particulates given off by burning diesel oil.

- Added safety is provided by its quick shutdown capability and the quick start-up would enable faster handling of trainees.

- It would have true training capability providing flexibility in changing the extinguishment and response times, thereby making a fire easier or more difficult to extinguish. A training session could be stopped at any point for corrective instruction and then continued. The system could also be adapted for remote trainee monitoring provisions.

## PROPOSED DESIGN APPROACH

A plan view of a proposed synthetic fire fighting trainer is shown in figure 28. An artist's concept of the proposed trainer is shown in figure 29. The proposed trainer essentially incorporates the pertinent design features and measured flame characteristics given in this report.

The prototype would use the extended horizontal burner nozzles to position the flame within the trainer with burner controls located outside the flame area. Flame deflectors would be used to spread the flames and minimize the number of burner units. It is envisioned that smaller size burners would be used near the door entrances to accommodate vertical nozzle positions or "goosenecking" type of hose handling maneuvers. A steel grating provides a simulated burning surface interface.

Burner units with individual control valves are grouped together where possible to use a common air supply to minimize the number of blower units and controls. Also the gas supply for each burner group would be obtained from a common header. This approach would improve reliability and cost by reducing the number of air and gas supply equipment.

Sensors to detect the extinguishment agent would be located away from the extreme flame environment. However it is noted that collectors are located near the surface grating to avoid errors in detecting an accurate location of the applied hose water (or other extinguishment agent). The quantity of sensors are shown in accordance with the number of burners, although multiple sensors may be considered to improve reliability and provide better sensor area coverage.

The control station would include the digital control unit for extinguishment and reflash conditions, a master shutdown control, and monitoring provisions for trainee performance.

Safety features would include automatic safety shutdown controls and a preventilation purge system. Also a safe path for trainees could be provided where the reflash mode (burner re-ignition) would not be used along a prescribed path.

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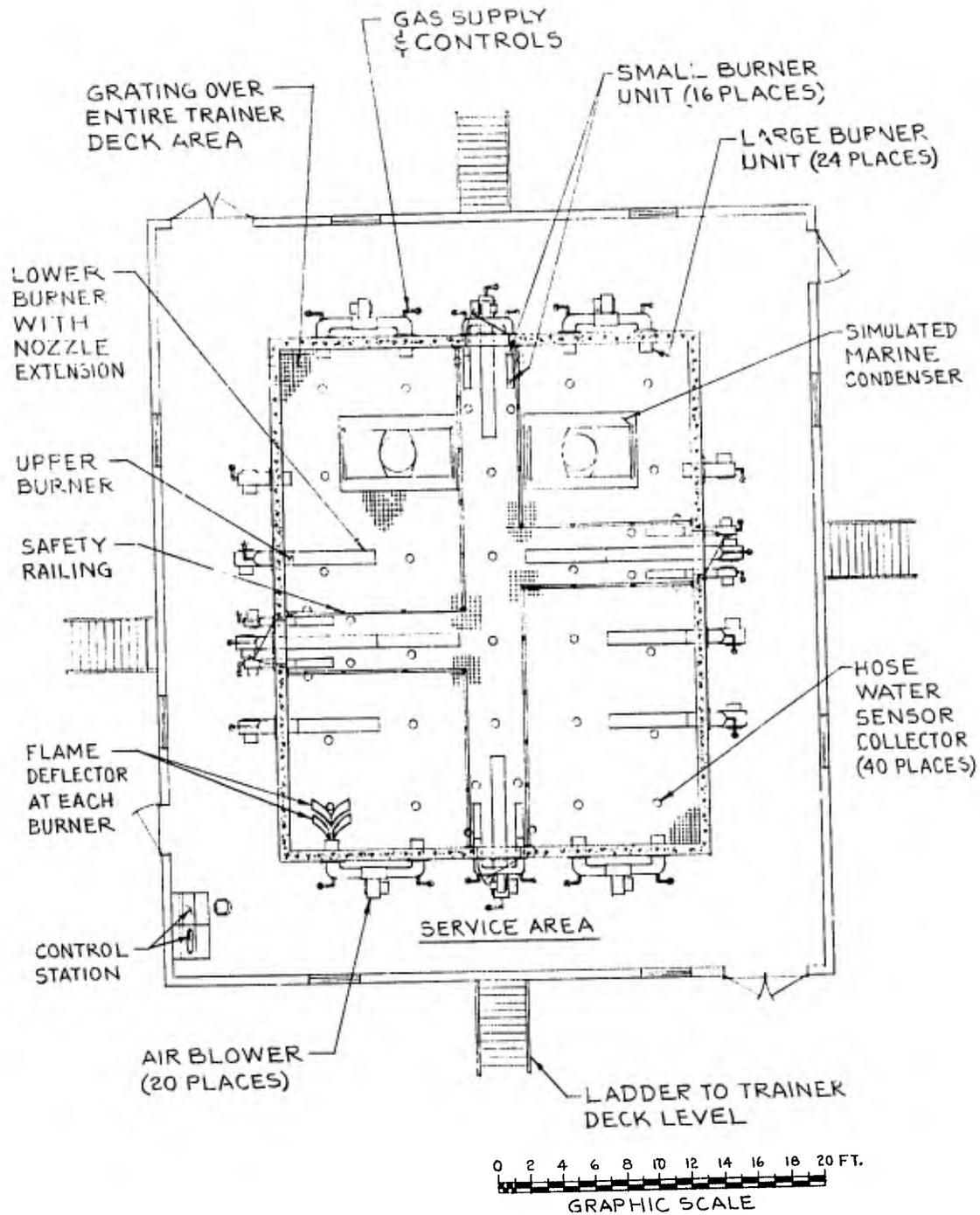


Figure 28. Proposed Burner Equipment Layout Plan

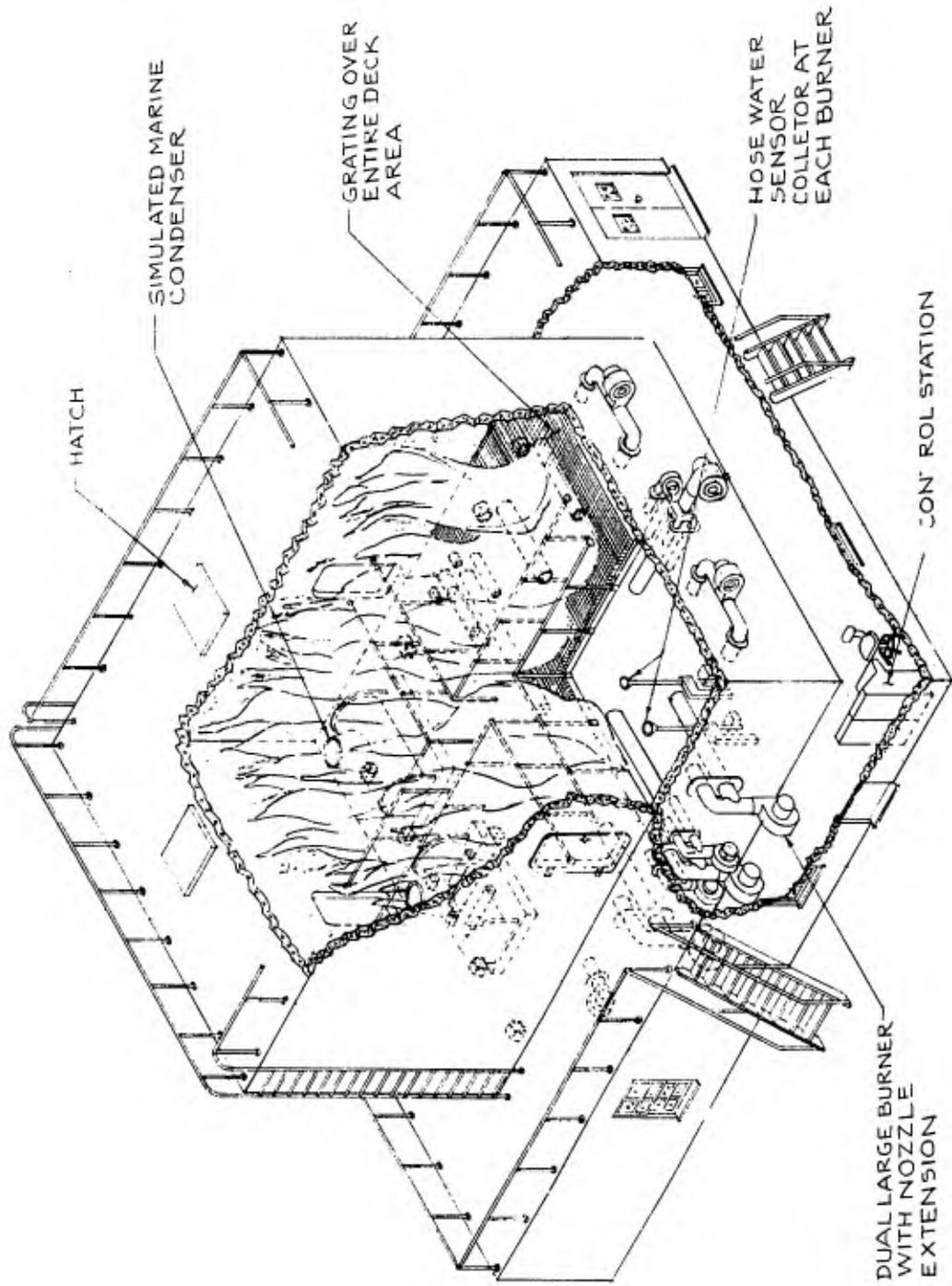


Figure 29. Artist's Concept of Proposed Synthetic Fire Fighting Trainer

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